Examining the Role of Blockchain in Enhancing Transparency and Traceability in Sustainable Supply Chains

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Abstract

Sustainable supply chains increasingly require verifiable transparency and end to end traceability to satisfy regulatory expectations, extended producer responsibility initiatives, and rising consumer demand for credible sustainability claims. This research investigates the role of blockchain in enabling trustworthy tracking and tracing across multi tier networks by creating an immutable, time stamped, and auditable record of product provenance, process steps, and compliance evidence. The study first conducts a structured literature review to identify dominant use cases, data elements, and performance metrics, and to synthesize technical, organizational, and legal challenges. Particular attention is given to data quality, participant incentives, privacy and confidentiality, scalability, governance, and the risk of recording inaccurate physical events. Building on these insights, the research develops an implementation roadmap that links architectural decisions such as consortium governance, permissioning, consensus choice, smart contract design, and on chain versus off chain data placement to supply chain objectives. The roadmap specifies interoperability requirements for integrating blockchain with enterprise resource planning systems and complementary Industry 4.0 technologies, including IoT sensing, digital identifiers, and analytics, so that physical events are captured reliably and translated into standardized digital records. The research concludes with design principles and traceability key performance indicators that support pilot to scale deployment and continuous improvement. Overall, the findings suggest that blockchain can improve transparency, reduce verification effort, and strengthen trust, but only when it is embedded in robust governance and aligned with disciplined data capture and process controls. These guidelines inform managers selecting platforms and prioritizing investments for supply chain value.

Keywords: Blockchain; Supply chain transparency; End to end traceability; Sustainable supply chains; IoT & ERP integration.

1 Introduction

Interest in product safety and quality, as well as regulatory, social, and economic concerns, has led to the implementation of traceability systems worldwide. However, the flow of information is reasonably dependent on transparency. Transparency is the provision of relevant, timely information without cost, delay, or discrimination (Kian et al., 2022, Mofatteh et al. 2026). Transparency in the supply chain2 can be achieved through the use of traceability. Several logistical measures need to be implemented in production alliances where economic relations are established between multiple distinct companies scattered across regional production facilities. A significant amount of communication is required since many different stakeholders must collaborate to achieve the common goal of value addition, in addition to the physical flow of resources for procurement, production, distribution, and transportation activities (Zhou, 2019). For this reason, logistics service providers play a crucial role in the supply chain and are required to provide various value-added services, such as organizing transportation. High-level communication, especially at supply chain interfaces, is shown to be essential for ensuring collaboration (Khan et al., 2022).

As a result of the introduction of process automation, business processes have shifted from manual to electronic communication and involve the use of innovative technologies. However, for a very long time, process design was limited to a centralized structure. There are several issues related to the adoption of suitable technology in centralized operations, such as blockchain technology (Al-Kassar & Singh6, 2019). One of the most critical aspects of using blockchain applications is monitoring social and environmental conditions to control and prevent safety and health issues (Adams et al., 2018). The adoption of blockchain technology throughout the supply chain offers an opportunity to ensure respect for human rights and fair working practices (Salmi et al., 2018, Mofatteh et al. 2025). For example, transparently recording product history assures buyers that the purchased products are sourced and produced in environmentally friendly ways. Smart contracts can be particularly capable of independently complying with regulations for monitoring and verifying sustainable policies and conditions (Sentobly et al., 2022).

Blockchain can eliminate supply chain intermediation, where fewer levels result in reduced transaction costs, reduced time, and reduced company waste in the supply chain (Chang

et al., 2019). Firstly, blockchain technology can ensure safety and authenticity by helping reduce resource consumption. For example, traditional energy systems have a centralized management model with high-pressure losses in highly extensive networks. In contrast, a peer-to-peer network based on blockchain technology can reduce network scope, thereby significantly reducing wasted energy over long distances and reducing storage facilities (Hu et al., 2020). As a result, several blockchain-based platforms aim to reduce supply chain waste. Secondly, blockchains can ensure that products sold as environmentally friendly are indeed so. An example is the certification program verifying the origin of approximately 740 million hectares of certified forests worldwide using blockchain technology. Thirdly, in the context of the circular economy, blockchain can ensure improved recycling performance. For instance, in Northern Europe, people are encouraged to recycle by offering rewards in the form of cryptocurrency tokens. In this regard, the blockchain-based Plastic Social Project has shown how plastic waste can be reduced by converting it into money (Sabri et al., 2019).

The fundamental challenges in using blockchain technology to enhance transparency and traceability in sustainable supply chains include the lack of appropriate infrastructure and the limited widespread adoption of this technology across various industries. Legal restrictions and the absence of clear standards for blockchain implementation in the supply chain are significant obstacles to the development of this technology. Additionally, organizational resistance to technological changes, implementation costs, and the need for education and awareness-raising among stakeholders are other existing challenges. From a research perspective, there are multiple gaps in examining the practical impacts of blockchain on supply chain sustainability, identifying local barriers, and providing localized models for this technology.

Moreover, studying the interaction of blockchain with other emerging technologies such as the Internet of Things (IoT) and Artificial Intelligence (AI) in optimizing the sustainable supply chain is a less explored research area. Given these challenges and research gaps, this study seeks to answer the main question: How can blockchain technology improve transparency and traceability in sustainable supply chains, and what are the barriers and solutions for its implementation?

Aims of the research

- Analyse and present opportunities, challenges, and goals in a sustainable supply chain with a focus on Tracking and Tracing
- Providing a roadmap for organizations' supply chains using blockchain for tracking and tracing
- Examining Blockchain's Ability to Address Sustainable Supply Chain Performance

Importance of the Research:

Lately, supply chains and the increasing demand for sustainability complexity have emphasized on importance of transparency and traceability. Companies and consumers are seeking assurance that environmental, human rights, and moral principles are being Followed to throughout supply processes. Blockchain technology, due to its characteristics like stability, decentralized data recording, and high security, can play an important role on improving transparency and traceability in sustainable supply chains. This technology can help reduce Deception, and resource waste by recording information at all stages of the supply chain, from raw material supply to final consumption. Plus, the ability tracking products create significant value by increasing trust among Partners, improving quality of the product, and optimizing processes of logistics.

Despite that, the acceptance and implementation of blockchain in the supply chain face significant challenges, including insufficient familiarity with this technology, legal restrictions, Structural challenges, and organizational hesitation to technological changes. So, evaluating the role of blockchain in enhancing transparency and traceability in sustainable supply chains, while identifying existing opportunities and challenges, will provide localized and practical solutions for implementing this technology.

Thus, to validate the importance of the present study, it is sufficient to state that blockchain technology will basically improve Clarity, trust, and efficiency in sustainable supply chains too which needs to develop and apply it to achieve international standards and reduce existing challenges. Additionally, considering the mentioned issues, one of the necessities of this research is to contribute to a better understanding of blockchain capabilities and provide localized models for its implementation in domestic supply chains. The results can

also assist policymakers, industrial managers, and researchers in making informed decisions and developing optimal strategies for utilizing this technology.

2 Literature Review

In this section of study, we will go through the theoretical background and the previously conducted literature. We will commence by defining the supply chain, then various types of supply chain, sustainable supply chain, supply chain specifications, and supply chain transparency. In the following chapter, we will discuss blockchain technology, smart contracts, the supply chain management application of blockchain, the role of blockchain to extend transparency, the role of blockchain to extend traceability, the economic, environmental and social dimensions of sustainability, challenges of sustainable supply chain, the role of digital technologies for supply chain sustainability, and where blockchain has its role in sustainable supply chain.

Theoretical Foundations of the Research

Supply Chain

The term supply chain refers to all the processes, operations, resources, institutions, and technological infrastructure involved in all phases from procurement of raw materials to production, distribution, and delivery of the product to the customer. It is internal and dynamic network along with outside organizations which engage in ceaseless interactions and coordination to deliver value to ultimate customers. In short, the supply chain initiates from raw materials suppliers and, traveling through various phases of production, warehousing, distribution, and selling, finally arrives at the ultimate consumer (Khanelarzadeh, 2024).

In recent years, productive supply chain management has received growing importance fuelled by intensified competitiveness, heterogeneity of customer needs, market globality, and cost pressures. It is through its emphasis on integrating and maximizing physical, informational, and financial flows through different chain components that supply chain management contributes to better organizational performance. Its main objective is to establish coordination and synergy among all the chain components in order to be able to react to market needs, drive customer satisfaction, lower costs, and raise productivity.

The supply chain consists of various components, all of which play critical roles in attaining overall goals. They entail raw material suppliers which ensure the inputs needed to manufacture the product, manufacturing units which process the inputs into final goods, distribution units and warehouses which house and prepackage goods for shipping, transportation and logistics networks which transfer the goods, and ultimately, the end consumers who buy and utilize the product (Sarshkeh et al., 2024).

Due to technology innovation and the rise of innovations like Internet of Things (IoT), big data analytics, artificial intelligence and blockchain, supply chain has been fundamentally transformed. They allow better identification, tracking, analysis and decisions, thereby making the supply chain more transparent, efficient, and responsive. Out of all these, blockchain technology has attained a particular status in contemporary supply chain management because of its attributes like data immutability, high transparency, data security, and the execution of transactions without middlemen (Uno et al., 2024).

Types of Supply Chains

Supply chains differ according to industry type, nature of product, complexity, and organizational strategies. This categorization is to better grasp the structures and choose suitable models for efficient supply chain management. Each has its specifications, merits, challenges and is utilized according to market conditions and the operational setting. Some of the most popular supply chain types are listed below:

- **Traditional or Linear Supply Chain**

In this kind of model, information is linear and hierarchical from the supplier to the manufacturer, distributor to the retailer and ultimately the end user. Communication among components is minimal and mostly one way and information transfer is slow. This model was prevalent before and is only suitable under stable environments (Busuona & Gebresenbet, 2023).

- **Lean Supply Chain**

The lean supply chain aims to reduce waste, maximize resources and save efficiency. It aims to eliminate nonvalue added activities, reduce inventories and deliver goods at the right time. It is appropriate in environments where demand is predictable and goods are standardized.

- **Agile Supply Chain**

The agile supply chain is both reactive and adaptable to quick changes in the market. It is appropriate for constantly changing life-cycle products, volatile demand, or high levels of customization. It calls for the capability to respond swiftly to market fluctuations and to work very closely with customers (Khan et al., 2022).

- **Hybrid or Lean-Agile Supply Chain**

This model is a mixture of lean and agile methods. The backward half works lean and productively whereas the front half is agile and flexible. It is appropriate for products where the manufacturing portion is standardized whereas there is another portion to be customized.

- **Sustainable Supply Chain**

It addresses at the same time economic, social and environmental aspects. It aims to minimize harm to the environment, encourage social responsibility and achieve economic gain. Some of the attributes include the use of renewable energy, reducing waste, reusing resources and adherence to ethical principles (Khan et al., 2022).

- Digital Supply Chain

Backed by IoT, big data, AI, machine learning, and blockchain technologies, digital supply chain maximizes visibility, coordination, and intelligent decision-making. It facilitates predictive analytics, live tracking, and is especially useful for dynamic management and beneficial in complicated and global scenarios.

Typically, the choice of supply chain model relies on the nature of the business, product type, request from the market and environmental uncertainties. A proper understanding of the models enables organizations to devise suitable supply chains resulting in sustainable competitive gains (Powell et al., 2024).

Sustainable Supply Chain

A sustainable supply chain is one composed of processes, relationships and activities among suppliers, producers, distributors, and customers which is governed under the three primary dimensions of sustainability: economic, environmental, and social. It is not just intended to satisfy market needs and maximize profitability but to reduce environmental degradation and promote social justice along the chain as well. Economic performance is still valued in this kind but is no longer the criterion of success. Instead, profitability is balanced with managing the environment and social equity (Lumen, 2024).

In the last few years, global concerns about climate change, pollution of the environment, resource discharge, and social inequalities forced companies to rethink conventional supply chain configurations. As far-reaching and long term planning, there has been the quest to improve efficiency and control costs amid curbing negative environment impacts and advancing rights and workers welfare, community, and stakeholders (Nwoyaku et al., 2024).

Within this context:

- **Economic sustainability** is all about productive use of resources, cost savings, improving performance and competitiveness.
- **Environmental sustainability** entails reducing pollution, employing clean energy, recycling, designing environmentally friendly products, and transportation optimization.
- **Social sustainability** entails adherence to labor rights, maintaining workplace safety, facilitating local communities, driving equality along the supply chain and ensuring fair and healthy working conditions.

Hence, the sustainable supply chain is a multi-faceted concept requiring an integrated effort, organizational commitment, collaboration from various stakeholders and embrace of innovative technologies. It not only ensures long-term profitability of the companies but contributes to brand reputation, customer happiness and achievement of global sustainable development goals. It ultimately connects economic performance with social accountability in the current competitive and challenging environment (Nwoyaku et al., 2024).

Characteristics of a Sustainable Supply Chain

As part of a holistic and contemporary practice of supply chain management, a sustainable supply chain has some unique attributes that differ from the conventional economically motivated schemes. Their attributes are aimed at tackling environmental,

social, and economic issues, and reconciling organizational interests with the well-being of society and the planet in the longer term.

One of the defining features is its co-consideration of all three pillars of sustainability economic, environmental, and social. In contrast to conventional supply chains solely aimed at cutting costs and economic efficiency, sustainable supply chains take into consideration environment-oriented goals (e.g., reducing emissions, using clean energy, reducing waste) and social ones (e.g., employee rights, safety levels, gender equality, and community assistance) as well (Dar et al., 2024).

One critical aspect is transparency and traceability. Organizations must document and report extensively about sourcing raw materials, the manufacturing process, transportation, consumption, and even recycling of the product. This transparency instils confidence among consumers and stakeholders and prevents unethical and illegitimate practices within the chain (Zeynivand et al. 2021).

Inter-organizational collaboration is critical as well. Rather than sheer competition, there is collaboration through partnership with suppliers, customers, governmental organizations, and NGOs to achieve common social and environmental outcomes. This collaboration provides opportunities for knowledge-sharing, co-innovation, and synergies in resources.

Additionally, digital technologies like IoT, big data, blockchain, and sophisticated information systems tend to be utilized by sustainable supply chain operations. Process optimization, greater transparency, minimized resource utilization, and better environmental performance are facilitated by the above technologies (atahi Valilai and Houshmand 2014, Soumya et al., 2025).

Other characteristics we have to take into consideration include flexibility and resilience. More resilient supply chains are in better positions to adapt to crises, climatic changes, market fluctuations, and changes in supply and demand. Organizations are safeguarded from economic and ecological risks through such flexibility; thus, they are in a position to sustain their sustainable development course.

Lastly, sustainable supply chains are forward-looking sustainable models prioritizing long-term value creation, resource preservation for generational purposes, and responsible ethics where conventional supply chains typically make decisions focusing

on short-term profits. This mindset gives rise to responsible performance and balanced development.

In short, the characteristics of a sustainable supply chain represent a multi-faceted, collaborative, and responsible management of the chain of value where economic profit walks side by side with protection of the environment and social welfare (Ahmed et al., 2024).

Supply chain transparency is the transparent, correct, and punctual access and sharing of information among all the actors along the chain. It ensures that one is able to view, track, and assess activities, material flows, information, and even decision-making processes along the supply chain. In the current complex and competitive environment, organizations are confronted with multi-layered and international supply chains where suppliers, producers, distributors, and customers have interactions in a networked configuration. In such environments, transparency is instrumental in fostering trust, enhancing coordination, mitigating risks, and boosting accountability.

By its very nature, transparency enables organizations to track every phase of the value chain—from raw material sourcing to delivery of the finished product—and remain aware of the suppliers' and other partners' performance in aspects like quality, compliance to the environment, ethical behavior, and adherence to human rights. Transparency fuels fact-driven decisions and helps to minimize the risk of concealed or improper behavior. Transparency, at the same time, is now poised to serve as a competitive tool—improving brand reputation, boosting customer loyalty, and attaining investor confidence (Shukla, 2025).

Additionally, transparency has direct implications for traceability. This is such that information about raw materials origin, manufacturing processes, transportation, and distribution channels is captured and kept in a manner that allows for quick and effective product or material tracking in the event of defects or recalls. This is very critical in industries like food, pharmaceutical, and textiles, where product defect will have consequential implications for consumers' health or brand reputation (Hosseini et al., 2023).

Through the assistance of information systems, digital technologies, and tools such as blockchain, transparency and traceability can reach a secure and unalterable level. Blockchain and digital technologies have revolutionized conventional supply chain

frameworks. Full transparency is not easy to attain, but it does require technological infrastructure, an open organizational culture, facilitating regulations, and an ethical commitment at all chain levels. Some may even resist transparency due to fear of revealing confidential information, losing competitive advantage, or distrust among partners (Apard et al., 2023). Hence, for effective transparency, there has to be parity between the disclosure of information and safeguarding business interests. Ultimately, transparency is not merely a means to accountability and risk management but one of the pillars of sustainability and innovation in contemporary supply chains.

Blockchain Technology

As one of the most revolutionary and disruptive technologies of the 21st century, blockchain technology provides a decentralized and distributed means to store and transfer data. It is basically a blockchain database made up of blocks with certain data stored in an immutable and encrypted form. Another characteristic of blockchain is the fact that, once a block is joined to the chain, data from it cannot be changed or modified—improving security, transparency, and authenticity in data transfer (Rezania & Mosayzadeh, 2023, Mofatteh et al. 2023).

First launched in Bitcoin, blockchain's uses soon broadened from the finance sector into industries like supply chain management, healthcare, energy, education, and intellectual property rights. One of its significant benefits is removing middlemen from transactions and establishing trust using cryptographic protocols and decentralized consensus. In conventional methods, data verification relies on middlemen or centralized institutions. Blockchain, however, provides trust through a decentralized network and mutual data verification by all members within the network.

Within the supply chain sector, blockchain is utilized to longitudinally and transparently document transactions and events along the product journey from raw material origin to the ultimate customer. Material source information, transportation conditions, quality certificates, delivery schedules, and other process information are documented in secure, decentralized format. All members of the supply chain have access, with no risk of data tampering or deletion. Transparency increases trust among consumers in brands, enhances corporate social accountability, and facilitates instant problem detection in crises like product recall (Sarshekeh et al., 2024). Other benefits of blockchain are lower monitoring costs, quicker data processing, automation using smart contracts, and

facilitating the execution of ethical and environmental standards. However, challenges like the necessity for sophisticated technological infrastructure, extensive energy requirements, scalability, and regulatory or legal issues still discourage its extensive use. In spite of all challenges, the increased approval of blockchain in different supply chains signals its great potential to increase sustainability, transparency, and efficiency. In the near term, it is anticipated to become an integral part of sustainable supply chains (Uno et al., 2024).

Principles of Blockchain Technology

Blockchain technology is founded on some very fundamental principles that distinguish it from other data storage and information transfer methods. Those principles are at the center of the working nature of the technology and assure data security, transparency, decentralization, and immutability. Decentralization is the foremost and most fundamental of all the principles (Radmanesh et al. 2023). In comparison to centralized databases, where data is under the authority of one controlling entity, blockchain distributes data across all members or nodes within the network. This sharing enhances security and reduces risks inherent in grouping information into one specific location (Lumen, 2024).

The second principle is immutability. Data written to the blockchain cannot be altered or undone. This is achieved through cryptographic linking of each block to the previous one in the chain, such that any alteration to one block will propagate to the subsequent blocks in a chain reaction, which will be marked as suspicious behavior to the rest of the nodes. This characteristic is well-suited to permanent and non-repudiable record-keeping. The second principle is immutability. Nobody is able to edit or erase recorded data from the blockchain. This is achieved through cryptographic linking of each block to the previous one in the chain, such that any alteration to one block will propagate to the subsequent blocks in a chain reaction, which will be marked as suspicious behavior to the rest of the nodes. This characteristic is well-suited to permanent and non-repudiable record-keeping.

The third is distributed consensus. In a blockchain network, no one party can confirm or deny a transaction independently. Instead, nodes authenticate and agree to the validity of transactions through some consensus algorithm such as Proof of Work or Proof of Stake. This practice promotes trust among members of open anonymous networks and

significantly reduces chances of fraud or wrongful data introductions (Soumia et al., 2025).

Principle four is known as Transparency and Traceability. Most blockchain platforms record common data to the same ledger to all network members. This type of visibility is total transparency of processes to the level that each individual's transactions or events are traced from where they originate to where they finish. However, various levels of access and privacy may come at a fee depending on the type of blockchain (public, private or consortium).

Advanced cryptography is yet another guiding principle behind the technology. All information on the chain is secured by secure cryptographic methods and user identities are verified digitally. This not only enhances the security of the information, but also decreases the risk of identity creation or tampering. All of these principles together have made blockchain a transparent, trustful, secure data-exchange system eliminating any third party. Applying blockchain to supply chains has the potential to enhance transparency as well as traceability, lower regulatory expenditures, and establish trust within all parties. It thus presents a solid base for sustainable supply chain implementation (Nouriakou et al., 2024).

Smart Contracts

Smart contracts are among the salient innovations of blockchain technology, largely revolutionizing the making of agreements, execution, and tracking thereof among parties. Written in programming languages like Solidity, they execute automatically once specific conditions are fulfilled. Put simply, smart contracts are blocks of code that automate and enforce an agreement's terms and obligations independently without the intervention of humans. Smart contracts were pioneered by Vitalik Buterin, the creator of Ethereum, and have been adopted extensively across finance, law, crowdfunding, and most obviously supply chain management. Smart contracts are employed mainly as tools to lower costs, speed up processes, and improve accuracy in economic transactions and business processes (Khanlarzadeh, 2024).

One of the most significant strengths of smart contracts is automation. All processes involved are automated once the smart contract is launched. For instance, in a sale contract, after digital verification of the payment by the buyer, the contract will autonomously execute the shipping of goods or services, and transfer of ownership will

take place without any delay. This hugely increases contract execution speed and avoids time wastage (Uno et al., 2024).

Security and transparency are some of the primary attributes of smart contracts. As they are hosted on the blockchain, all transactions and interactions are noted on the public, immutable ledger. This enables all parties to view the execution status with ease and confirm the data is correct. For example, upon shipping of the product, data like shipment date, payment status, and other contract specifications are traced and made transparent. Further, data and contract specifications cannot be modified once they have been registered because blockchain has its default cryptographic protection. This gives great data protection and avoids fraud and tampering.

Reducing expenses could be considered as another important advantage of smart contracts. In traditional methods, contract execution usually involves the intervention of intermediaries such as lawyers, banks, finance bodies, or legal bodies—each charging extra fees. With smart contracts, such intermediaries are bypassed, and all contract verification, execution, and monitoring are done internally through the parties themselves, which translates to great cost efficiency. This is very beneficial in complicated and multi-level sectors, such as supply chains where approvals are always necessary at every level (Lumen, 2024).

In addition to adaptability and flexibility brought about by the means of smart contracts, one may refer to more advantages and/or opportunities provided by smart contracts. For instance, one could claim that they can adapt to variant types of agreements and therefore, be adjusted once a specific requirement is needed. Smart contracts can also deal with straightforward transactions like the sale of goods. Moreover, they can handle more complicated agreements like financing, insurance, foreign exchange, and even contracts between organizations. These features make smart contracts a very beneficial asset and of great value in supply chains where a lot of contracts are in effect at the time.

One of the key factors of smart contracts is decentralization and sustainability. In conventional setups where data and agreements are maintained centrally, blockchain distributes data and agreements to thousands of nodes across the globe. This decentralized nature is what ensures nobody, nor any outside party, is able to manipulate the data or access it without authority. In return, smart contracts have maximum

credibility and trust, as each party is certain about the fair and proper execution of the contracts (Hosseini et al., 2023).

Within the supply chain context, smart contracts are critical. They will track the overall supply process from supplier to customer automatically. For example, the smart contract will automatically monitor transportation status, deliver confirmations, and payment status updates when a product is delivered. This gives everybody involved—producers to buyers—complete visibility. In addition, if agreed conditions are not satisfied (e.g., payment is late, goods are not received), the smart contract will initiate compensatory actions like product replacement or refunds.

Lastly, there is programmability and fine control. Organizations have the ability to set explicit rules and criteria for specific situations. For instance, during transportation delay, there is the capability to program the smart contract to autonomously take corrective measures. In conclusion, with characteristics such as automation, high security, transparency, cost savings, and flexibility, smart contracts have the potential to transform business and economic processes. In the supply chain, they increase efficiency, lower complexity, and ensure trust among parties. With such characteristics, smart contracts have an important role to play in enforcing sustainable and transparent supply chains (Rezanian & Mousizadeh, 2023).

Applications of Blockchain in Supply Chain Management

As one of the cutting-edge technologies, blockchain has now come to play a critical role in bringing efficiency, transparency, and security to supply chain management. With its distinctive characteristics—namely decentralization, high security, and transparency in data—blockchain has the potential to streamline all sorts of processes within the supply chain. Some of the most important uses of blockchain in supply chain management are discussed below:

Increasing Transparency and Traceability

One of the key challenges in supply chains is insufficient transparency and product track-and-trace. Blockchain raises the level of transparency at every phase of the supply chain. Each product movement and each transaction is logged to the blockchain transparently and cannot be altered, making it possible for all parties to track the condition of any product at any specific time. This is particularly important for the supply

of risky or perishable items like pharmaceuticals, foodstuffs, or high-end goods that necessitate strict monitoring (Nvariako et al., 2024). All parties can access information about the product's current location, manufacturing timelines, transportation phases, and so much more using blockchain. For example, manufacturing organizations are able to properly validate which supplier provided the product, at what time and under what conditions.

Minimizing Cost and Delays

Traditionally, there are many processes involved in validating and accounting for transactions, which often have to go through middlemen like banks, agents, or notary services. Not only do middlemen add expense but they also delay processes. Blockchain avoids the middleman by having transactions recorded directly to a decentralized ledger, thus making processes cheaper and faster (Lohmann, 2024). This is extremely useful in payment and settlement within the supply chain. Payments are made automatically and under specific conditions only, using smart contracts, with consequent cost reduction and easing of delay.

Improving Data Security

One of the key benefits of blockchain in supply chain management is its security. All data and transactions in the blockchain are encoded and kept in multiple dispersed nodes. It is therefore virtually impossible to access data or manipulate information without authorization. Any data modification will require all the copies to be changed across the network. This makes forgery of data very hard. In supply chain management, data protection is very important, particularly in preventing fraud, forgery, or modification of information concerning product authenticity, expiry dates, or product specifications. Blockchain offers a secure data storage system where all parties have access to dependable data and information (Khan et al., 2022).

Managing Payments and Contracts with Smart Contracts

Smart contracts, one of the central aspects of blockchain, have the capability to execute contracts and transactions without any human intervention within the supply chain. As pre-specified conditions must be satisfied before the operation is executed, they autonomously execute contracts and transactions within the supply chain. A payment, for instance, can be executed automatically by a smart contract as and when goods are

delivered to the recipient. Smart contracts provide assurance of all processes in the supply chain being transparent and executed automatically, cutting delays and ensuring all parties honor commitments (Sarshekeh et al., 2024).

Anti-Fraud and Counterfeit Activities

Counterfeiting and fraud are serious problems in supply chains, most common in sectors such as pharmaceutical, food, and luxury. Due to its immutability and transparent record of transactions, blockchain is very effective in overcoming such problems. For instance, every product entering the supply chain can have a unique digital identity, and every aspect of its manufacturing, transportation, and distribution will be transparently noted down on the blockchain. This digital identity enables verification of the authenticity of a product and fraud prevention by producers, consumers, and others (Soumia et al., 2025).

Improved Inventory Management and Supply Optimization

One of the areas where blockchain is of much help is in management and optimization of inventory. With blockchain, managers have access to real-time and correct information concerning levels of inventory, delivery schedules, and demand along the supply chain. This information enables managers to make improved decisions about production, procurement, and distribution, eliminating stock shortages or excess inventories.

Improving Supplier and Customer Relationship Management

All transactions among suppliers and companies or customers can be traced and logged through blockchain. This helps supply chain managers to assess how well suppliers perform and take better decisions about procurements. It also helps the customers to see transparently where and how their goods are progressing with each order and delivery (Shukla, 2025).

Comparing and Assessing Suppliers

Having rich and transparent data on the blockchain facilitates simple comparison of the quality, price, and timeliness of various suppliers, making it easier for companies to choose the best suppliers and establish business relationships founded on true data and information they can trust (Appard et al., 2023).

Blockchain to Make Things More Transparent

Ultimately, blockchain helps bring about transparency in regulatory and legal processes. Organizations in various countries and sectors have to adhere to particular

laws and regulations that call for transparent and correct reporting. Blockchain, by storing data in an immutable and publicly accessible ledger, facilitates the generation of correct, real-time reports which are readily available to regulatory bodies and governments. This enables organizations to prove compliance and steer clear of legislative issues (Hosseini et al., 2023).

In total, blockchain with its distinctive attributes like immutable data documentation, transparent transactions, improved security of data, and the absence of go-betweens considerably increases supply chain transparency. The characteristics enable organizations to deal with their supply processes better and avoid drawbacks like fraud, delay, and customer rights violations. In addition, transparency provided by blockchain increases trust among all stakeholders involved in the supply chain, which therefore better ensures its overall output.

As a revolutionary and disruptive technology, blockchain is instrumental in making supply chain transparency better. Transparency in this context entails offering all parties relevant and credible information pertaining to goods, services, processes, and business transactions. One of the challenges many industries have is low levels of transparency in many supply chain processes, which results in fraud, defects, legal compliance issues, and inventory management issues. With its decentralized nature, uneditable data, and transparent information storage, blockchain substantially mitigates such challenges and increases transparency at all levels of the supply chain (Khan et al., 2022).

One of the critical areas where blockchain enhances transparency is in product traceability during the production, transportation, and distribution phases. It is often tricky to keep tabs on products from origin to destination in conventional supply chains—particularly if they go through various suppliers and transportation phases. Blockchain allows for all the information about a product, such as production time, delivery date, transportation conditions, and each stage's location to be captured transparently and immutably in a distributed ledger. As such, any user or organization with access to the blockchain is in a position to easily and correctly confirm the status and authenticity of a product at any given time (Ahmad et al., 2024).

This transparency and traceability feature is most beneficial for industries where the product must be strictly monitored, e.g., pharmaceutical, food, and luxury goods. In the case of pharmaceuticals, for example, many of the products have to retain certain

conditions under transportation, and failure to retain such conditions might affect their quality and efficacy. With blockchain, any product condition changes—whether temperature changes or even changes in the environment—can immediately be tracked and made visible to all the parties in the supply chain.

Blockchain also increases supply chain financial transparency. Payment delay, fraud, and payment disputes among suppliers, manufacturers, and buyers are typical financial problems. Blockchain presents a transparent and tamper-proof record of finance where all transactions are traced and recorded transparently. Blockchain prevents fraud and abuse of finance and payment disputes. In addition, smart contracts, which are executed automatically under pre-defined rules, speed up payment and prevent payment delay (Bosona & Gebresenbet, 2023).

Data security within blockchain is similarly intertwined with transparency. In conventional setups, data is susceptible to unauthorized access or tampering, resulting in decreased transparency and trust. Blockchain, however, keeps data in encrypted format at various distributed nodes, with unauthorized changes or deletion being almost impossible. This allows all parties within the supply chain to access valid and secure data. This is mainly important for confidential data like product expiry dates, particular shipping requirements, or accounting records.

One of the reasons why there is transparency in blockchain is because intermediaries are eliminated. In conventional supply channels, most processes depend on third parties to approve transactions or transfer information from one group of interested parties to another. Intermediaries are time-consuming, expensive, and vulnerable to abuse or mistakes. Blockchain reduces the costs incurred, increases speed, and simplifies processes by removing the role of intermediaries and facilitating direct recording of transactions in one common, transparent ledger—increasing transparency at the same time (Dar et al., 2024).

The Role of Blockchain in Enhancing Traceability

Blockchain is one of the groundbreaking and revolutionary technologies responsible for boosting traceability in supply chains. One of the primary challenges in supply chain management is tracking goods from origin to destination correctly and transparently. For most industries—particularly where product quality, safety, and authenticity have to be

ensured, e.g., pharmaceuticals, food, and luxury goods—traceability is of utmost significance. Blockchain increases product traceability and supports transparency and trust at every level of the supply chain through the decentralized and irreversible documentation of all data and transactions (Soumya et al., 2025).

One of the salient aspects of blockchain is its decentralized nature. In conventional systems, data is usually stored in central databases, which is prone to tampering or modification. Blockchain, however, distributes data to many nodes, holding data safe and secure. Information is stored immutably, and every time the product passes through to another phase in the supply chain, there is an addition of a new and verifiable record in the ledger. Therefore, all the parties involved—from suppliers to customers—can effortlessly view the entire record of the product movement and any alterations in its condition (Upadhard et al., 2023).

Blockchain can even track the exact time and geographic location of each product at every step of the supply chain. For any movement, say during transportation, blockchain will record the time and specific date of loading, shipping conditions, and current geographic position. This data may include temperature, humidity, and various environmental conditions—most importantly for delicate items like medicines or perishable food. Finally yet importantly, the information is accessible at any time, from anywhere, to provide better overall traceability in the supply chain.

Smart contracts applied to blockchain also add to better traceability. They are run automatically according to pre-established conditions and have the capability to record any shift in the status of a product—whether its entry into a warehouse or its movement to its ultimate endpoint. This ensures that all parties have access to correct and current information, eradicating faults and preventing misuses (Khanlarzadeh, 2024 [Hijri: 1403]).

One of the benefits of blockchain in traceability is total transparency at all levels of the supply chain. In conventional systems, data might be concealed or indirectly disclosed. Blockchain, however, accounts for all transactions and alterations pertaining to product in an open and transparent ledger. This allows all parties—from producers to consumers—to see thorough and verifiable information concerning the status of a product. This is very useful when two factors such as authenticity and quality are needed, as in the case of luxurious items or organic farm products. For example, consumers are

able to scan the QR code or barcode to gain information on the origin of the product, date of production, and transporting history (Sarshokh et al., 2024 [Hijri: 1403]).

Traceability is also enhanced from a regulatory standpoint by blockchain. Food, pharmaceutical, and environment-related industries, in particular, are tasked with making meticulous reports of product traceability. Blockchain allows for transparent, tamper-free, and accurate reporting, facilitating regulatory bodies to ensure compliance with legislation and standards. This facilitates faster audits and inspection and avoids fraudulence or managerial misstep within the supply chain.

Ultimately, by offering monitoring and transparency functionality across the supply chain most specifically within the process of traceability blockchain helps build higher levels of trust between consumers, suppliers, and all the parties involved. Because blockchain information is immutable and tamper-evident, all involved parties have confidence in knowing the information is legitimate, real, and current. This not only obliterates challenges like fraud and abuse, but also increases efficiency, reduces costs, and increases the customer experience. Overall, blockchain is a valuable component in maximizing traceability and facilitating improved, more transparent supply chain management (Powell et al., 2024).

Dimensions of Sustainability (Economic, Environmental, Social)

Sustainability is the capacity of the system to satisfy current as well as future demands without harming resources and the environment. Dimensions of sustainability typically encompass three primary aspects: economic, environmental, and social, which collectively represent a sustainable system. All the above-mentioned dimensions are discussed in detail below:

Economic Dimension of Sustainability

The economic aspect pertains to such ideas as profitability, productivity, and economic viability in organizations and industries. In sustainable supply chains, the focus of the economic aspect is how an organization or firm is to achieve long-term profitability alongside managing resources productively and conserving resources to minimize waste. This entails embracing economic measures that not only guarantee profit but also concern cost cutting and efficiency improvement. In all this, maximum resource optimization, minimization of waste, process optimization, and value creation by

technological innovations—such as blockchain, artificial intelligence algorithms, and automation—feature prominently. In addition, decisions in the economic aspect should reflect long-term visions and steer clear of short-term pressures likely to jeopardize immediate profitability. This means there should also be adherence to economic transparency, risk mitigation, and formulating a business model that persistently generates value (Rezania & Mousizadeh, 2023).

Environmental Dimension of Sustainability

Environmental dimension encompasses the impact of economic, production, and business operations on the environment. A key objective in the dimension is controlling negative environmental consequences, which may encompass such actions as greenhouse gas emission reduction, maximizing the utilization of natural resources, managing wastes, and reducing the level of pollution. Organizations in sustainable supply chains must specifically focus energy, water, and raw materials consumptions and pursue solutions to limit such consumptions.

One of the primary characteristics of this dimension is carbon management. Organizations have to take measures like optimizing transportation processes, using clean energy resources, and reducing production waste. Moreover, the circular economy, which focuses on utilizing recycled materials and goods as opposed to producing fresh ones, is one very important practice for enhancing the environment's sustainability. Other significant measures in this dimension are utilization of green technology like clean energy, low-energy machinery and equipment, and producing low-carbon goods. Blockchain may enable better management of energy and resource utilization in the supply chain and thus curtail the environmental effects (Hosseini et al., 2023).

*** Social Dimension of Sustainability**

Social dimension refers to the social responsibility of corporations and organizations including impact on community, employee or any other stakeholders. This category applies to the area of human right, employee welfare and corporate social responsibility. They need also to be more targeting working conditions, decent living wages and job security on one side and uplift of working class living standards and social welfare on the other.

On the social side, CSR (corporate social responsibility) is believed to be instrumental. CSR is all about a corporate entity's commitment to contribute towards the betterment of the social and welfare environment of the local society. For instance, enterprises could have a significant social role to provide workers' education, respect social programs, for example: to build schools and hospitals (Apard et al., 2023).

In addition to the points mentioned previously, this dimension revolves around social justice, human rights, and diversity and/or inclusion. For this to be fulfilled, what is needed is providing healthy working conditions, preventing all types of injustice and discrimination, and improving the living conditions of local communities. In supply chain contexts, organizations must make sure that their suppliers also follow these principles. In other words, profitability must not be the only concern and there must be enough attention paid to employee rights and social conditions as well.

Integration of Sustainability Dimensions

The economic, environmental, and social dimensions are intertwined and must all be addressed at the same time to achieve a sustainable supply chain. For example, economic efficiency can come with decreased energy and natural resource utilization during production processes, which conversely contribute to lower levels of impact on the environment. Conversely, better social treatment of employees and neighboring communities increases the level of production and adds value to the organization. Ultimately, attaining a sustainable supply chain entails having an integrated view focusing all of these dimensions as one and attaining balance from all the dimensions to ensure it is economically feasible, environmentally sustainable, and socially responsible (Shukla, 2025).

Issues of Green Supply Chains

Challenges of sustainable supply chains are the issues that may obstruct and complicate the smooth implementation and management of sustainability measures in the supply chain. The challenges usually pertain to balancing economic, environment, and social needs of sustainability, which, collectively, contribute to intricate and conflicting requirements. Some of the most important challenges are as follows:

Costly and short-term profitability

One of the main challenges in sustainable supply chain implementation is high costs linked to it. It is common for companies to adopt strategies with higher short-term profits, while sustainable practices entail higher initial investments. Some of the expenditures may include research and development costs for green innovations, the introduction of new technologies, or changes in the process of manufacturing to minimize harm to the environment. More stringent monitoring and setting up of intricate management systems is also demanded by sustainable practices, which add to the costs (Ahmad et al., 2024).

Complexity in Coordination and Collaboration Across Suppliers

Sustainable supply chains call for extensive collaboration among manufacturers, suppliers, and distributors along the entire supply chain. Harmonizing these parties to sustainability targets—particularly where they have dissimilar culture norms and standards—can prove extremely tough. Variances in social and natural environment liability regulations from one country to another and from one geographic area to another complicate efforts to have a supply chain working in sync with sustainability goals at all levels (Soumya et al., 2025).

Legal and Regulatory Barriers

In most countries, there are not yet well-established legal and regulatory regimes pertaining to social and environmental concerns to underpin sustainable supply chain schemes. Fragmentation in the regulations, ambiguity, and regulatory uncertainty mean there is likely to be confusion and barriers to organizations seeking to adopt sustainable practices. In addition, the fact there are no agreed global standards for monitoring and measuring sustainability—most notably at international level—is a significant problem, with likely implications for delay in decision-making and the development of sustainability policies (Ahmad et al., 2024).

Challenges around Data and Transparency

A primary challenge within sustainable supply chains is data collection, storage, and analysis. Transparency is one of the key principles of sustainability, but obtaining both accurate and up-to-date data at each phase from suppliers to consumers is challenging due to inadequate infrastructure, absence of data standardization, and various actors in the supply chain's unwillingness to provide data. In some sectors, in particular, attaining data about working conditions and environmental practices of suppliers in various countries is very challenging.

Lack of Technological Infrastructure and Innovation

Sustainable supply chains usually call for sophisticated technologies to increase efficiency and reduce environmental consequences. Yet, for the majority of industries, employing technologies like the Internet of Things (IoT), blockchain, and sophisticated information systems is in its nascent phase, and most organizations are not in possession of the finances or infrastructure to take advantage of such technologies. Further, the

deployment of such technologies tends to call for deep changes in current processes and high organizational readiness for innovation (Soumya et al., 2025).

Conflicts Between Economic and Social Objectives

Economic and social goals are often at odds with each other. For instance, even though using low-cost labour in lower-income nations is economically viable, it is against social welfare and human rights principles. Companies are likely to encounter ethical and social accountability challenges arising from such conflicts. This balance is one of the challenges in attaining sustainable supply chains (Dar et al., 2024).

Environmental Risk Management

Sustainable supply chains face a large number of risks in dealing with the environment. Climate changes, resource shortages, and ecological emergencies usually have a negative impact on the sustainability of supply chains. Raw material availability, transportation, and distribution, for example, are impacted by changes in climatic conditions, which may bring about disruptions. Coping with such risks and coming up with measures to manage environmental crises is one of the most critical challenges to sustainable supply chain management (Loman, 2024).

Shift in Consumer Conduct

Consumer behavior is yet another driving factor in encouraging the development of sustainable supply chains. Despite the increased demand for sustainable goods, consumers might still have to contend with increased costs and unavailability of sustainable alternatives. This might slow the general acceptance of sustainable supply chains. In addition to that, transforming customer behavior and sensitizing consumers to sustainable goods remains an ongoing challenge in this sector.

The Role of Digital Technologies in Supply Chain Sustainability

Digital technologies have been identified as the catalyst for transforming sustainable supply chains, where they play a critical role in the performance of the supply chain. They bring innovative solutions which help maximize different processes of the supply chain while facilitating monitoring, transparency, and accountability at all levels of the chain. Some of the foremost digital technologies shaping supply chain sustainability include blockchain, the Internet of Things (IoT), artificial intelligence (AI), big data, augmented and virtual reality, and robotics. They help to curb the environmental footprint, heighten social

interactions, heighten transparency and traceablity, and maximize the utilization of resources (Nowariaku et al., 2024).

One of the leading technologies of sustainable supply chains is blockchain. It keeps every transaction duly noted in a digital, decentralized ledger so all information is transparent and unalterable. This helps prevent fraud and corruption in supply chains and facilitates the tracking of goods along the chain with even greater accuracy. Blockchain brings accountability and transparency to resource purchases, particularly in sectors where social and environmental standards are paramount (Powell et al., 2024).

The Internet of Things (IoT) connects sensors and devices to digital networks. Accordingly, it makes it possible to collect data in real-time concerning product condition and ambient conditions. This makes monitoring of operations possible in detail. In the case of the delivery of perishable goods, for example, IoT sensors can monitor humidity and temperature levels during shipping, preventing spoilage and encouraging more efficient resource utilization (Khan et al., 2022).

Artificial intelligence and machine learning are also important components of sustainable supply chain management. They allow companies to predict demand, manage resources productively, and optimize inventory. They help to model different scenarios and predict possible problems, thus lowering risks and costs while reducing waste and maximizing resource efficiency.

Big data and advanced data analytics are potent contributors to supply chain sustainability. They enable organizations to examine business consumptions and different trends, which in return facilitates strategic decisions. In particular, advanced analytics is able to highlight process inefficiencies and maximize resource utilization, thus optimizing organizational performance.

Augmented reality and virtual reality are innovative technologies benefiting sustainable supply chains by mimicking different processes and enabling companies to test system performance with accuracy. For instance, employees may utilize VR to familiarize themselves with complicated processes or utilize AR in monitoring goods and operations in real time (Sarshoke et al., 2024).

Robotics and automation play an important role in sustainable supply chains as well. Robots are utilized in warehouses, manufacturing lines, and transportation to improve efficiency and decrease energy and labor requirements. Companies have the capabilities

to perform processes better, quicker, and with reduced effects on the environment. This is very helpful in sectors looking to lower energy consumption and enhance productivity.

In short, digital technologies lead to sustainable supply chain transformation in terms of efficiency, transparency, risk management, and resource optimization. With the implementation of such cutting-edge tools, companies are able to achieve environmental and social sustainability along with boosting economic and competitive strengths (Lumen, 2024).

The Position of Blockchain in Sustainable Supply Chains

As a cutting-edge technology, blockchain plays a key role in revolutionizing sustainable supply chains. With its characteristics—transparency, security, and traceability—blockchain provides efficient solutions for improving sustainability in supply chains. Transparency, reduction of environmental footprints, and social responsibility enhancement are of utmost importance in sustainable supply chains. Blockchain offers a secure base to store immutable and decentralized data, facilitating extensive monitoring and tracking of different resources across the supply chain (Khanlarzadeh, 2024).

One of the most salient attributes of blockchain is its transparency. In green supply chains, data pertaining to production, shipping, and usage of goods needs to be easily and accurately available. Blockchain ensures all the actors involved—producers, suppliers, consumers, and regulatory bodies—receive access to information at the same time and at the same level of transparency. It helps all the phases of product and service delivery to be traceable and transparent, preventing fraud, improper conduct, and corrupt acts within the supply chain.

A key role is played by blockchain in enabling the traceability of goods and products along the supply chain. Any product, from production to delivery to the ultimate consumers, is recordable and trackable in any decentralized ledger. This feature is particularly significant for supply chains carrying perishable and environmentally sensitive products, such as food and drugs. Blockchain is able to track delivery time, temperature levels, and transportation conditions, offering immutable and transparent information to all interested parties (Sarshoke et al., 2024).

Additionally, blockchain helps mitigate resource utilization and environmental footprint in supply chain sustainability management. It streamlines complicated and

expensive processes and is even able to automate transactions and contracts. With the utilization of smart contracts—self-executing contracts with no requirement for human intervention—processes like payment, resource deployment, and delivery of goods may be executed with better accuracy and timeliness. This provides energy efficiency and resource preservation (Uno et al., 2024).

Finally, blockchain increases social responsibility along supply chains. By anchoring data in the blockchain, producers and companies can openly prove that goods are produced under environmentally and socially responsible conditions. This is especially important to consumers and regulators looking for credible information about production and sourcing. In sectors like fashion, food, and pharmaceuticals, where social and environmental concerns are at play, consumers increasingly require assurances about the social and environmental footprint of goods—responses to which blockchains are well-suited.

In summary, blockchain has a facilitatory and revolutionary impact in green supply chains. This impact is achieved through blockchain's encouraging of transparency, traceability, efficiency in resource utilization, and social accountability. Together with digital innovation, blockchain leads to greener and efficient supply chains (Bosona & Gebresenbet, 2023).

Novelty and Innovation of the Research

The existing research into the role of blockchain in improving transparency and traceability in sustainable supply chain does not appropriately consider the localization of blockchain in sustainable supply chain solution. The originality of the current research is the introduction of an overall methodology for the analysis and localization of blockchain technology in sustainable supply chains. Challenges and opportunities in this environment are examined in this paper that establishes a localized and pragmatic approach place-based model for decentralized initiatives to deploy Blockchain in sustainable supply chains.

Another innovative aspect of this work is the investigation of blockchain's effects on the economic, environmental, and social dimensions of supply chain sustainability — dimensions that were given minimal consideration in existing research. In addition, with an analysis based on methods and case studies across a range of industries, the research

is assessing the actual effects of blockchain deployment and offering practical recommendations and decision-making tactics tailored to various contexts.

This study provides a rich picture about the advantages and challenges of the blockchain technology and is helpful in shaping sound strategies for both policy-makers and industry executives when establishing an effective climate of innovative culture. Consequently, this study constitutes a rare example of innovation, with regards both to its object and method complexities.

3 Methodology

3.1 Research Method

The current research is applied with respect to its purpose and descriptive-analytical with respect to data collection. With respect to the character of the data, it is a mixed-methods design that involves both quantitative and qualitative data.

Applied Research Method

Applied research is a form of research done to solve immediate needs and challenges that exist within society. It is contrasted with basic (or fundamental) research and, to a certain extent, is based on it. That is, each applied research normally has a basis in basic research, though not necessarily vice versa.

Applied research comprises different types, and comparative research is, according to a number of scholars, a subcategory of it. Applied research is meant to resolve specific issues or to present innovative solutions to issues encountered by individuals, groups, or communities. The method is normally viewed as a scientific or traditional research method, as it involves the practical application of scientific methods to actual issues of concern.

While carrying out applied research, a research worker investigates a hyporesearch with caution to pinpoint a specific issue and further puts the hyporesearch to the test using experiments. Often, with the help of empirical methods, this research method tackles actual issues.

Descriptive Research Method

Descriptive research provides a systematic and accurate description of a population, condition, or phenomenon. It provides answers for the questions of what, when, where, and how, but is not intended for answering questions with a "why" at the beginning—experimental research methods are used for those types of questions instead.

Both quantitative and qualitative methods may be applied when designing descriptive research to study variables. Unlike research that is experimental, the variables are neither controlled nor manipulated by the researcher but are rather observed and appraised. Quantitative and descriptive methods are used in descriptive research. The research design, for the purpose of ensuring validity and reliability of the research findings, has to be formulated to a high degree of accuracy.

Analytical Research Method

Analytical studies are research that investigates the researcher's hyporesearch on the relationship between variables. It is basically a study where the researcher specifies and establishes the kind of relationship that there is between exposure and outcome.

Analytical method involves a thorough analysis of a broad spectrum of issues and their relationship to each other. It stems from a richer comprehension of variables and their dynamics. It is a method, which quite usually borrows from psychology techniques, that permits the analysis of issues that could have arisen over time within an individual's life that could be a hindrance to the fulfillment of their potential or achievement of their goals.

3-3 Research Method and Data Collection Tools

In carrying out this study, and taking into account both its objectives and the nature of the subject under review, a library-based strategy was employed to obtain the required material. A broad selection of dependable scholarly sources, drawn from both domestic and international contexts, was examined in detail. These included academic books, peer-reviewed papers, graduate theses, research reports, and established scientific databases. The information assembled from these varied materials formed the groundwork for the theoretical discussion and was gradually shaped into the analytical framework on which the present research rests.

3-4 Research Scope

Thematic Scope: It is about the contribution that can be provided by blockchain technology towards the development of higher degrees of traceability and transparency in sustainable supply chains. Working under this theme, the study is about concepts and categories such as sustainable supply chains in themselves, the technical and

operational nature of blockchain, traceability and openness issues, and the three broad sustainability aspects of economic, social, and environmental.

Geographical Scope: As the process of the inquiry solely relied upon reading published literature, no such geographical cut-off date existed for the collection of the material. Publications in relation to the study were gathered from the national sources, in combination with publications from wider international settings.

Temporal scope: All sources and data up until the spring of 2025 have been considered in the current study.

3-5 Statistical Population and Sampling Method

Since the present study is library-based and documentary research-based, it does not involve a conventional statistical population or sampling method (i.e., sampling managers or industry experts). In practice, the population to be analyzed consists of authentic scientific and research sources like books, articles, theses, and scientific reports. The sampling method in this study was purposive, based on the selection of credible and relevant sources to provide a comprehensive description of the role of blockchain technology in sustainable supply chains.

3.6 Data Analysis Method

In this library-based research and analytical study, data were collected and analyzed by reviewing academic sources, articles, reports, and books on blockchain technology and sustainable supply chains. The purpose of this section is to identify the drivers for the enhancement of transparency and traceability in sustainable supply chains using blockchain technology and to develop an analytical framework for the identification of the strengths, weaknesses, opportunities, and threats concerning the research subject.

Data analysis was carried out by two important techniques:

1. Qualitative Analysis:

Existing research and scientific literature was examined in detail to facilitate the simplification of the identification and categorization of pertinent concepts, theories, findings, and experiences of green supply chain and blockchain. Major internal and external variables influencing the system were inferred from the data collected, which served as the basis for developing a SWOT analytical framework.

2. Conceptual and Strategic Analysis:

On the identification of internal and external drivers, SWOT matrix was utilized to analyze strengths, weaknesses, opportunities, and threats. The analysis was qualitative and descriptive in nature with the purpose to derive strategic inferences and conceptual recommendations in order to maximize benefits and mitigate constraints.

3.6.1 SWOT Technique

SWOT analysis, which stands for Strengths, Weaknesses, Opportunities, and Threats, is a popular analytical method in strategic planning used to identify internal and external factors affecting a system.

Qualitative SWOT analysis was conducted in the current research based on a comprehensive review of scientific literature. The following steps were undertaken:

1. Internal Environment Analysis (Strengths and Weaknesses):

Scientific sources and current journals were studied in the attempt to reveal the strengths (its positive sides and virtues) of blockchain towards sustainability-oriented supply chains, and the obstacles (its negative sides and flaws) towards it:

2. External Environment Analysis (Opportunities and Threats):

The drivers for effective implementation of blockchain were identified to be the opportunities (i.e., technological innovation, legislative reform and market revolution) and threats (i.e., legislative, monetary and environmental threats) by the examination of the literature and available sources.

3. Development of the SWOT Analytical Framework:

The factors outlined were grouped and explained in a manner to formulate a framework in examining and comprehending the interactions between the internal strengths and weaknesses and the outside opportunities and threats. It is what is used in conceptualization in providing conceptual tools and strategic advice on how to apply blockchain in green supply chains.

3.6.2 Strategic and Conceptual Analysis

From the SWOT framework and literature review, potentially suitable strategies were conceptually and qualitatively derived. It is the aim of analysis in the present paper to provide recommendations that shall allow organizations and supply chains to improve transparency and traceability by utilizing the strengths of blockchain while balancing its weaknesses.

This integrative and descriptive analysis comprises the following elements:

• Strengths analysis to leverage opportunities and neutralize threats.

• Identifying their weaknesses and presenting methods of overcoming their influence through leveraging external strengths.

• Formulating conceptual strategic proposals for the maximization of the efficiency and effectiveness of blockchain technology towards sustainable supply chains.

3-7 Research Reliability

Library research reliability entails the authenticity and truthfulness of the used source and the scientific literature provided. Reliability in research is therefore an assessment of the extent the researcher is able to obtain, examine, and interpret data accurately and consistently. Utilization of credible sources and corroborating evidence through the reading of academic books, refereed journals, and technical journals is the overall means of attaining reliability in analytical and library research.

In order to make the study reliable, the following steps were taken:

Reliable and current sources: Only technical and academic sources in reputable databases and journals were used.

Comparison of data from various sources: Similar data and information were compared, examined, and verified from various sources to ascertain their consistency and accuracy.

Systematic and rigorous data analysis: Collected data were analyzed qualitatively and analytically, and respective concepts and factors related thereto were established in an organized and documented manner.

Correct use of sources: All the facts and the analysis can be traced and verified from references from real sources.

By following such standards, it can be stated that the results and the analysis, which has been conducted in this study, are very credible and reliable and, hence, serve as a strong basis for deriving conceptual framework and policy guidelines.

3.8 Enhancing Transparency and Traceability in Sustainable Supply Chains:

The contemporary complex world depends significantly on supply chains to be the business determining factor and the lifeblood of the services and goods exchange.

Traceability and transparency are increasingly among the top determinants of supply chains of health, trust, and sustainability inasmuch.

Transparency refers to the availability of the most recent, comprehensive, and reliability information on operations, product movement, and supply chain management decisions. Transparency refers to a trait that allows stakeholders to be able to obtain the ongoing status of operations and react quickly and conveniently in terms of changes, problems, and hazards. Non-transparency will surely cause mistakes, lag, excessive cost, and loss of trust by customers, counterparties, and other stakeholders.

traceability meaning is locating and following up the raw material or product from the point of origin all the way to the point of destination. Identification of the sources, transportation, manufacturing, and distribution are made easier through traceability. traceability is necessary where the business is in the foodstuff, drug, and sensitive material where the integrity, quality, and safety of the product are ensured, and in case of a disaster, e.g., product recall, the response is accelerated.

Last but not least, traceability and transparency boost the operational effectiveness, but they are just as extremely critical from the sustainability point of view. As the Earth becomes increasingly aware of the environmental and societal impacts of production and consumption, the customers and the authorities demand more and more sustainable supply chains. In this context, emerging technologies such as blockchain facilitate the secure and tamper-evident documentation and sharing of information, which possess a very high potential in enhancing traceability and transparency in sustainable supply chains (Saberi et al., 2019).

Despite the utmost advantages of blockchain to boost the traceability and transparency of supply chains, technology is still plagued by several significant limitations and challenges that undermine its full potential. The first constraint is that of scalability and transaction processing speed; blockchain platforms in the public domain can process a very small number of transactions within a single second, which becomes a bottleneck in large and complex supply chains where numbers of transactions and amounts of data processed within a day can be substantial, thus rendering the whole system inefficient.

In addition, the cost of implementing and the operational cost of the systems is an important constraint, particularly in the case of the industry environments with

heterogeneous or decentralized IT infrastructure. Such costs amount to financial investments in infrastructure development, labor, and routine system refurbishment—financial losses most organizations, particularly the medium and small organizations, cannot incur. In addition, the need for superior technical capabilities in the integration of the blockchain technology and the common supply chain infrastructures is a serious constraint that necessitates high-level capabilities and coordination among the supply chain components. However, the concern about security and privacy is pertinent; despite the very nature of openness and non-reversibility in blockchain technology, public operation of blockchain networks hosting sensitive business information and private personal data raises pertinent concerns, more so considering the fact that such high-level technologies remain in toddler development stages. Vulnerabilities to unauthorized access, the leaks of data, and abuse of data create challenges inhibiting the trust of the users. Secondly, legal and regulatory challenges tend to be observed; in most scenarios, the legislation and regulation of the blockchain-based supply chains remain cryptic or incoherent across nations, exposing the supply chains to legal complexities that can be adverse in the adoption of technology. Lastly, organizational and cultural barriers in the adoption of new technologies can hinder effective utilization; the executives and workers can resist utilizing the blockchain due to the lack of knowledge or perceptions about the complexity in the system.

Though the blockchain can ensure data immutability, data quality and correctness are still a vital challenge. If the input data is bad, incorrect, or flawed, the blockchain is not providing transparency and traceability. I.e., the “garbage-in, garbage-out” problem is a main vulnerability, reminding us of the necessity of strict data gathering and verifications. In addition, non-universal standardization of data formats and blockchain protocols inhibits data exchange among businesses and supply chains. Thus, the extent of big-scale, across-the-board collaborations is limited. Environmental factors are the outcome of the energy costs in the case of some consensus algorithms, e.g., Proof of Work, potentially running counter to the supply chain's sustainability goals.

Finally, despite promising evidence, blockchain remains in the early stage of widespread adoption throughout all industries. Most solutions used remain pilot schemes or limited projects, and very little research investigated their performance and success over the long term under actual-market conditions. Overall, leveraging blockchain’s

potential for improved traceability and transparency in supply chains more comprehensively requires further advancements in the underlying technologies, standardization, regulation sophistication, as well as additional stakeholders' education and training in a manner that overcomes the existing barriers and enables sustainable, large-scale usage (Casino et al., 2019).

The Concept of Product Digital Passport in Sustainable Supply Chains

The "product digital passport" is a novel sustainable supply chain management concept that has attracted plenty of attention over the past two years. It's a revolutionary innovation that plays an important role in the improvement of transparency, traceability, and information exchange along the supply chain among stakeholders. What is a product digital passport? It is an end-to-end digital file with the full and current information of a product, from the time when it's produced to when the product retires. Such information is stored securely and in its original form in technologies like blockchain, so the information is secure, trustworthy, and readily retrievable. What technology does is enable concurrent access to the information on the raw material origin, manufacturing process, transportation, refurbishment, and recyclability of the product. While doing so, it not only maximizes traceability but also helps achieve the sustainability and circular economy targets (Bader et al., 2021).

By the establishment of a coordinated and standardized information recording and exchange system, the product digital passport avoids information fragmentation and common vulnerabilities of the ordinary systems, generally concerned with the data storage in distinct and inefficient databases. Secondly, the product can enhance the consumer's confidence through the publicity of the chain of the product's consumption and production, enhancing competition and corporate image. Despite that, the application of a product digital passport entails the wide coordination of the supply chain stakeholders, data harmonization, and explicit legal provisions, being one of the most critical innovation challenges.

Moreover, world-level privacy and data protection requirements, technicalities in integrating disparate systems, and robust infrastructure demands are among the challenges in the universal application of product digital passports. Nonetheless, despite all this, innovation in new technologies such as blockchain, the Internet of Things (IoT), and artificial intelligence provides suitable platforms for theorization and

conceptualization of this concept. Some of the research concluded that product digital passports can efficiently support supply chain regulatory and reporting functionalities, lower administrative expenses, and increase product traceability and transparency (Geissdoerfer et al., 2020).

Aside from the supply chain rationalization, the technologies are applied for various economic and environmental purposes, including waste minimization, resource rationalization, and recycling and reuse. In most sensitive sectors like in the automotive, electronics, and food industries, it is definitely a must. The product's digital passport, in principle, is one exemplary innovation in the management of the sustainable supply chain that, in the guise of the traceability and visibility optimization, forms the basis for further innovation in the creation of the digital and green economy. But the realization of the whole potential of technology depends on international cooperation, the creation of common standards, and the eliminating barriers in the form of regulations and technologies, all of which require the sustained efforts of researchers, policymakers, and industries (Bader et al., 2021).

Usage of the Product Digital Passport (PDP) within the green supply chain is a new offer of greater transparency, traceability, as well as control of information, thereby making the whole supply chain efficient and reliable. One of the most important values yielded out of usage of a PDP is the end-to-end accuracy in tracing the product, thereby quality and whence the product is originating could be traced at all points of time. It makes companies react to challenges in the form of counterfeiters, fraudsters, as well as non-compliance in the form of environmental and societal requirements, thereby establishing greater trust among customers and others.

Furthermore, the PDP facilitates effective decision-making in the supply chain optimization and resource preservation in the availability of adequate and supportive information, in a position to instigate the minimization of wastage, reduction of the utilization of energy, and maximization of productivity. In addition, the PDP is instrumental in the facilitation of the achievement of a circular economy in which the product's superior and effective recycling, remanufacturing, and reuse are realized. Another benefit of the PDP is in the facilitation of the achievement of national and global sustainability needs and corporate social responsibility acts, which remain vital in the world competitive economy (Müller et al., 2021).

Despite such advantages, roll-out of the PDPs is an exercise beset by a myriad of challenges, whose serious examination is warranted. Pre-eminent among such challenges is technicality, based on the necessity of high-end infrastructure in data storage, capturing, and assured processing of big volumes of data. Protection of data against aberrant usage in the life cycle, more specifically in the case of a big supply chain with a large number of players whose clearance for access is variable, is an emergent necessity and an problematical issue. Besides technical challenges, management and organizational challenges are no less; management and organizational challenges are a time-consuming exercise and a man-intensive exercise, in terms of coordinating efforts amongst a myriad of players, in terms of normalization of information, and in terms of evoking a commitment amongst all the players for introducing new technology. At national and international levels, legal and policy constraints, such as failure of well-rehearsed paradigm of the governance and ownership of internet data, can potentially snuff out roll-out and development of the technology. Roll-out and operation cost of the PDP systems, which can prove inhibitory and prohibitive, the more so in the case of medium- and small-sized units, is a cause of concern in terms of targeted funding and facilitatory policies. And, finally, the issue of substance of the problem of the matter of the substance of the problem of the non-interoperability and enablement of a myriad of technologies in the supply chain gives rise to problematical technical fixes and universal standardization, which means that successful roll-out of the PDPs will be a phased exercise.

Yet, as a transformation technology, the PDPs are critical to the creation of sustainable supply chains and promise enormous benefits in supporting transparency, managing risks, and enhancing environmental and economic performance. It becomes necessary for the full technology potential to be leveraged through cross-sector collaboration, technical and regulatory definition, and IT infrastructure investment in a shared effort to meet the challenges at hand and create better, transparent, and sustainable supply chains (Bader et al., 2021).

Already, application of PDPs in sustainable supply chains has brought numerous success stories and case examples in various sectors, witnessing the positive effects of the technology towards improving transparency, traceability, and data handling across a product life cycle. The automotive sector is one example. Volkswagen and BMW, among the rest of the industry players, have applied the use of PDPs in the improvement of spare

part traceability and the sustainability of the supply chain. By maintaining data regarding the origin of raw materials, the process of manufacturing, repairing, and recycling precisely for every component, such corporations have boosted stakeholder and consumer trust while improving environmental regulation compliance.

In the same manner, the clothing and fashion business, after experiencing issues of fraud, labor exploitation, and environmental degradation, adopted the PDPs in tracing raw materials and making ethical productions across the supply chain (Walmart, 2022). Patagonia and H&M offer clear information regarding raw material sources, productions, and the factory labor, allowing consumers to make informed choices and providing product sustainability and ethical conformity (Walmart, 2022).

Food and agriculture case studies offer the potential of PDPs in ensuring accurate, real-time product traceability from farm to table along the supply chain. For the companies handling the produce and distribution of organic and perishable products such as Walmart and Carrefour, they harnessed the use of this technology in improving supply chain visibility, product quality and safety, and wastage reduction due to spoilage and improper handling. These examples show that, aside from improving transparency and traceability, PDPs can offer opportunities in automating internal business procedures, improving risk handling, and attaining sustainability goals (Carrefour, 2022).

On a research basis, several case studies authenticate that success of the PDPs relies on coordination among organizations, technology adoption among the stakeholders, establishment of IT infrastructure, and the availability of supportive legal frameworks. Ineffective coordination among the SC players and the lack of uniform data protocols can be major impediments. Secondly, research further suggests that firms actively encouraging a digital innovation context are likely to have greater success and returns on IT investments in the case of the PDPs.

In the end, such examples and case studies expose the ability of PDPs to serve as a primary tool for delivering responsible and sustainable supply chains, as long as technical, managerial, and legal hurdles are adequately comprehended and addressed. In addition to the enablement of increased transparency and traceability, the technology itself optimizes operations, minimizes wastage, and enables stakeholders trust a primary objective of the world's sustainable development (BMW Group, 2021).

4 Discussions over the results

Analysis of Weaknesses and Threats (SWOT)

Given a general evaluation of blockchain's impact on facilitating transparency and traceability across sustainable supply chains, a vulnerability and threat identification is a significant and essential step. SWOT analysis—preciated for its value as a strategic management tool—facilitates a greater grasp of current challenges and limitations through a consideration of internal and external influencing factors. The section responds to the internal vulnerabilities and external threats involving the use of blockchain across sustainable supply chains, seeking to suggest better strategies for controlling them and minimizing associated risks. Precisely identifying weaknesses—like technological weaknesses, poor infrastructure, implementation challenges, and organizational resistance—enables policy-makers to pinpoint areas to be improved, formulating measures to increase organizational and supply network preparedness. Conversely, external environmental threats—like possible economic, political, legal, and cultural factors—can frustrate the complete advantages of blockchain and create possible challenges to its effective use.

At this point, regarding data compiled from a variety of sources together with supply chain expert information coupled with the technology involved on blockchains, weaknesses and indeed the risk are identified and categorized. The above serves as a milestone towards the next section on research, where solutions correspondingly and counter-strategy will be proposed towards the concept of reducing weaknesses. The above analysis serves as a significant aspect towards making decisions convenient and acquiring additional consciousness on implementing blockchain on sustainable supply chains.

Identification of Weaknesses

One of the essential steps in SWOT analysis involves identifying internal weaknesses, thereby better grasping the constraints and challenges hampering the realization of blockchain technology's advantages in sustainable supply chains. Organizational or supply chain network weaknesses are internal issues that could hamper effectiveness,

boost costs, or retard process speeds, thereby inhibiting the total realization of the advantages of blockchain.

- **Technical Complexities and the Need for High-Level Expertise**

In spite of the far-reaching opportunities that exist with the use of blockchain technology in providing increased transparency, traceability, and security in supply chains, it also has immense technological complexities that act as the major challenge inhibiting its effective use. The designing, building, and installing of an effective blockchain system call for an in-depth and multidisciplinary understanding of topics like chain data structures, cryptographic algorithms, smart contracts, mechanisms of consensus, and distributed network architecture. These call for an array of interdisciplinary skills in information technology, computer science, cybersecurity, as well as software engineering.

But most organizations working in supply chains, particularly small-medium enterprises, do not have access to trained, specialized experts. Also, there are constraints in accessing learning resources and training programs to acquire these skill sets. Even when organizations have such experts, the technological sophistication of blockchain causes an equally time-, money-intensive process of learning and adaptation. On top of challenges posed by technological knowledge, an emerging technology like blockchain continues to evolve, demanding iterative update of knowledge and skills.

In addition, maintaining and supporting blockchain systems involve high levels of sophistication and expertise, where coding errors in smart contracts or weaknesses in security measures can lead to system functionality losses that cannot be reversed. Such levels of technological sophistication and expertise needs are also a primary deterrent to the viable application of blockchain technology to green supply chains, where detailed planning on a level of educational needs, employee recruitment, and human resource development investment are essential.

- **Lack of Advanced and Suitable Technological Infrastructure**

Digital networks are built on information technology infrastructure, specifically advanced technology like blockchain. Infrastructure plays a key and decisive role in both quality and effectiveness. In sustainable supply chains, adequate and advanced technology infrastructures, e.g., fast communication networks, large capacity data centers, large capacity hardware, and strong cybersecurity, are essential for realizing the

potential value of using blockchain technology. However, the current state in most organizations and industries -- in particular, developing countries and regions -- speaks to inadequacy or unsustainability of such infrastructures. Inefficient infrastructures can hamper the speed of their blockchain network's transactions, limit its bandwidth, and reduce overall network performance through insufficient storage. Additionally, if such infrastructures lack security and reliability, organizations become liable to cybersecurity breaches and subsequent loss of confidential information, which is paradoxical; the nature of blockchain allows for trust, while this problem reduces trust amongst users and stakeholders.

In many supply chains, this infrastructure gap ends in unsuccessfully implementing or has major preventing challenges in implementing blockchain projects. Building, and upgrading such technological infrastructures incurs significant costs, planning, and monetary resources, usually interrupted, despite the best efforts toward introducing a new technology, by limited resources, other priorities within the organization, etc. Moreover, the incompatibility between the existing technologies/infrastructures and the underlying technology for blockchain causes additional barriers to coherence of systems, interoperability, thus lowering efficiency. In conclusion, a lack of sophisticated technological infrastructures is one barrier that could stymie the evolution of blockchain through supply chains in the sustainability context from reaching its full potential.

- **High Initial Costs and Investment Requirements**

A significant barrier to using blockchain technology in sustainable supply chains is the large up-front costs and investments needed to establish the systems. While most other conventional information technologies consist of starting a small application, starting a blockchain platform is a large sunk cost through its numerous components. Networking costs consist of buying servers, networking components, and advanced data centers that can provide processing and storage capabilities to deal with the large amounts of decentralized data and transactions. Software and development costs consist of writing custom protocols, writing smart contracts, and configuring consensus algorithms—in all cases engaging experts and lengthy development periods. Additionally, a large portion of the costs will be dedicated to staffing training, tech support, and project management. Finally, maintenance, upgrading, and troubleshooting costs while using the system

remain very high since blockchain is rapidly evolving technology that typically necessitates regular maintenance.

For the majority of organizations, and especially SMEs and actors with thin margins within the supply chain, it is reasonable to assume that organizations do not have the capacity to fund these costs most of the time, if not all of the time. As a result, organizations will delay or cancel any blockchain project. There is also a lack of real economic studies and strong business cases on the topic, which creates anxiety on the part of dollar investors and operators, and increases the financial risk of trying to do a blockchain based project. The financial barrier, in addition to the technical complexity and infrastructure barriers, does create real impediments to the uptake of blockchain into sustainable supply chains. Making progress on bringing these barriers down will require a combination of sound planning, public policy, and the private sector's involvement.

- **Shortage of Skilled Personnel Familiar with Blockchain Technology**

Among the key internal challenges of adopting blockchain technology in sustainability-oriented supply chains, the shortage of qualified personnel stands out. Because blockchain is both innovative and highly specialized, it requires experts and engineers who not only have strong foundations in information technology and computer science, but also possess a deep understanding of cryptography, smart contracts, consensus algorithms, and distributed networks.

In most organizations and industries, this blend of skills is rare. Without such specialized talent, the design, implementation, and ongoing maintenance of blockchain systems can be severely hindered. Training and upskilling existing staff is possible, but it is often time-consuming and costly—and many organizations lack effective training programs to build these capabilities in-house. This talent gap not only slows the rollout of blockchain initiatives, but can also compromise the quality and security of deployed systems. For this reason, organizations must prioritize investment in recruiting, training, and retaining qualified personnel. Doing so will allow them to maximize blockchain’s potential benefits while minimizing risks linked to technological weaknesses.

- **Organizational Resistance to Change and Adoption of Emerging Technologies**

When a fresh technology like blockchain steps into the office, it rarely gets a red-carpet welcome. More often, it runs headfirst into a wall of skepticism. That reluctance is one of the main reasons so many digital transformation plans fizzle out before they ever really get

going. Doubts creep in from all directions—some managers fret about workflow disruptions, others wonder if the tech will actually prove its worth, and plenty of people can't help but think about the risk of job cuts if too much gets automated. In truth, it's not hard to see why; most of us feel a little safer clinging to what we already understand.

In the world of supply chains—where hierarchies tend to be rigid and processes tangled—those same hurdles can feel like mountains. If innovation isn't part of the company's DNA, or if employees haven't had the mental runway to get used to advanced tools, blockchain projects move at a snail's pace, and quality inevitably takes a hit. The trouble deepens when leadership offers no clear direction, no visible backing, leaving teams adrift until the whole initiative stalls or simply withers away.

Overcoming that resistance is not luck, it is intentional. Good change management helps. So do training programs that meet people where they are. You should involve employees in the conversation before big decisions are made. Important to the process of aligning attitudes is being direct: explaining not only that blockchain affects their work, but why it is important and how it can make everyone's work better. If you do all of these things reasonably well, you may see skepticism transform into curiosity and even pride, which may alter the workplace from one that is avoiding a new technology to one that is leaning into innovation.

- **Scalability and Performance Issues in Blockchain Networks**

While blockchain technology is extremely useful for creating greater transparency and data security, supply chains face one of the most impactful technical limitations, scalability and performance, which may not result in widespread adoption and use. Blockchain networks vary in transaction speed and capacity to scale. This is mainly due to their decentralized operating model which requires achieving licenses on all nodes in the network. The drawback to this is that as the number of transactions in a blockchain network grows so too does the time to make a block to validate and time-stamp the transactions occurring in the network. An additional concern are certain consensus mechanisms like Proof of Work (PoW) and their energy consumption, which have opened the door to scrutiny about the environmental ramifications, operations budget and sustainability for the future. Also, the limited amount of data per block that allows quick scalability does not lend itself to performing agile scaling on a network. There must be technical recommendations to scale such as methods of sharding, Layer 2 technologies

or other consensus mechanisms the informed are willing to use who can focus on advancing blockchain technology. Specifically, since supply chains have high data and transaction volumes, the scalability and performance concerns just described represent serious issues. If they remain unaddressed, they can lead to considerable delays, increasing costs, and lowering stakeholder satisfaction.

- **Security Concerns and Data Privacy Protection**

While blockchain technology is the most secure way to store and transmit data due to encryption and decentralization, there are significant further issues with data privacy and integrity in sustainable supply chains. To begin with, in most blockchains, transaction data is completely publicly available and can have the costly consequence of compromising sensitive firm data and proprietary business-related information. In addition to simply affecting the firm, transaction data may be vulnerable to malfeasance by competitors in the marketplace as well as malicious actors. Similarly, while blockchain networks include some access control and data privacy mechanisms, stakeholders have legitimate privacy concerns, which necessitate the secure design of policies that safeguard privacy, requiring sophisticated plans beyond cryptography. By comparison, cybersecurity infrastructure failings, including 51% attacks, network breaches, and smart contract vulnerabilities, represent continuing and significant risks all of which inhibit adoption of blockchain technology by organizations (including the components of security and legal standards surrounding the acquisition of secure data).

- **Lack of Clear Legal Frameworks and Standards**

Another major obstacle to the implementation of blockchain technology in eco-friendly supply chains is the absence of clear and consistent legal rules and standards. Due to the relatively new and evolving nature of blockchain technology, the vast majority of countries and jurisdictions have yet to enact comprehensive legislation on the application of this technology, legal requirements, data ownership rights, and conflict resolution mechanisms regarding this technology. Lack of particular laws and regulations creates legal uncertainties that result in legal and financial risks for businesses. This places businesses in complex legal positions, creating doubt against the technology and aversion to investment. Furthermore, standardized technical and operational procedures assuring interoperability and consistency of the blockchain technology with other technologies as well as supply chains have not been fully developed. Inasmuch, this lack not only inhibits

the development and spread of the technology but also leads to fragmentation and inconsistency in implementations, hence inhibiting realization of the fundamental goals of the technology.

- **Incompatibility with Existing Systems and Processes in the Supply Chain**

One major aspect regarding the implementation of blockchain technology is that the chain cannot be compatible with existing systems, processes and software across the supply chain. Companies tend to have resource management, data capturing and functional systems that have been developed and geared for success over many years, not to mention it is difficult to change these systems for blockchain enabled platforms where there is a challenge of upfront complexity. A lack of compatibility could lead to a total overhaul of the IT and/or procurement infrastructure, leading to substantial change in the workflows as well as the organizational structure which would result in challenges in time, cost as well as technology. Another layer of complexity comes from the non-standardization of data formats and procedures when considering transferring data and the movement of information between blockchain systems and established systems. These challenges not only represent significant risks in the implementation of blockchains but make it harder to realize the full capability of blockchains when exploited within the supply chain. Therefore, it will require integrated solutions to link blockchain technology to established systems and workflow, which is likely to require significant investment, develop research, and cross-industry engagement.

- **Limitations Related to Processing Speed and Transaction Delays**

Due to the characteristics of consensus mechanisms and its decentralized nature, blockchain technology has systemic issues in speeding up transaction processes, including time delays, which can be particularly troublesome in supply chains with high volumes of transactions. In centralized systems, where confirmed transactions can happen faster (e.g. it can happen in milliseconds), in blockchain technology, every transaction has to be confirmed by the majority or all the nodes in a network, thereby taking longer before the transaction is ultimately written. The time delays can render supply chains less efficient, as decisions can occur somewhat slowly, which is concerning and potentially problematic when decisions need to be made quickly. The constraints imposed on the size of each block is problematic, as only limited amounts of transactions

and timeframes could be written, putting a strain on the network. Ultimately, it could lead to transaction backlogs, increased transaction / gas fees, and result in users (including organizations) adopting alternative technologies that are sometimes complementary. Therefore, addressing speed issues together with transaction delay problems continues to be a major hurdle in the evolving process of blockchain technology being adopted into operational contexts with high transactions, like sustainable supply chains.

- **Limitations Related to Processing Speed and Transaction Delays**

Among the significant issues with blockchain technology, its constraint in speed in transacting and latencies in registering its data remains an important limitation when dealing with practicality in industrial use cases like supply chains that are sustainable. The technology's decentralized nature and reliance on consensus algorithms in securing and verifying its information implies that it has inherent constraints when dealing with the number of transactions it processes. In larger public blockchains, each transaction must be verified by numerous nodes, thereby causing it to take longer to complete and register transactions. Moreover, the number of its data and block capacity are limited, causing it to process only few transactions per unit of time. This offers constraints in efficiency with rising response time, most importantly in supply chains where real-time and fast-processing information dictates industrial and managerial decisions. Transaction-processing latency could also lead to network congestion, rising payable transaction fees, thereby reducing the incentive for its use. Accordingly, improvement in scalability with higher speeds in transaction remains an important need when dealing with its creation and large-scale use in supply chains.

- **Complexity in Managing and Updating Smart Contracts**

Smart contracts, as self-executing programs in the blockchain, can also provide useful means of automating supply chains and increasing their efficiency. However, like with all new technology, managing and updating them presents serious challenges that present significant operational and technology constraints. First, smart contracts are typically written code that when deployed onto the blockchain cannot be edited, modified, or changed because the immutability found with the blockchain architecture ensures its transparency and security. The aforementioned trait becomes an issue when attempting to change rules, add functionalities or fix logic errors because managing smart contracts

becomes complex, time-consuming, and at times impossible. The second point is that lack of clear waste and vulnerabilities with the rules, application logic, or smart contract programming, could lead to an economic loss, even the failure of the supply chain system, and once these problems occur it would be very difficult to figure out they existed or fix them with the blockchain technology. The third point is the lack of a standard framework and application protocol interfaces, effective application development, and building blocks for smart contracts, added to the complexity for developers who were building smart contracts, but also added risk of making mistakes in those contracts. All in all, the smart contract development and management for updates needed a method, solid quality assurance frameworks, and supporting scalable future technologies, or there was a risk these smart contracts could become the main challenges, barriers to widespread adoption and use of the blockchain in the supply chain.

- Challenges Related to Full Transparency Without Compromising Sensitive Information

One of the major characteristics of blockchain technology is enabling complete transparency in recording and tracing transactions and data, which plays an important role in sustainable supply chains. While realizing this complete transparency without endangering the sensitive and confidential data of organizations and stakeholders is one of the intricate and subtle tasks of this technology, in most cases, the data written onto the blockchain could contain significant business information, industrial secrets, or users' confidential information, where uncontrolled disclosure or access to such information could result in adverse effects like unfair competition, violation of users' right to privacy, or damage to the reputation of organizations. While, in contrast, the permanent and immutable property of blockchain data implies that once written, it's difficult to delete or modify sensitive information. This requires the creation of sophisticated mechanisms like sophisticated encryption, confined access to data (Permissioned Blockchain), or the use of smart contracts in order to secure access. Another issue in this context is the establishment of trust among all members in the network in order to comply with the requirements of protecting the data without unauthorized disclosure. Consequently, realizing complete transparency onto the blockchain without sacrificing the security and right of privacy requires sophisticated design, advanced technological solutions, and corresponding legal and ethics frameworks, where this is acknowledged as one of the

crucial issues facing the realization and application of blockchain technology in supply chains.

Table 4-1: Weaknesses

Row	Weakness Title	Brief Description
1	Technical proficiency and the need for advanced-level abilities	Includes advanced technical skills in cryptography, distributed networks, and smart contracts
2	Insufficiency of advanced and adequate technological infrastructure	infrastructure Lack of fast communication networks, strong data centers, and adequate hardware in organizations
3	High set-up costs and investment	High investment required in hardware, software development, training, and system upkeep.
4	Shortage of skilled human resources with an understanding of blockchain	Shortage of experts with experience with blockchain and associated technology, requiring specific training.
5	Resistance to organizational change and accepting new technology	Resistance to change, fear over jobs, and lack of organizational readiness in accepting new emerging technology.
6	Scalability issues and network performance limitations	Limited speed in the process of transactions and increased latency in decentralized blockchains.
7	Security and data privacy concerns	Exposure of sensitive data, cyberattacks, and access management challenges within blockchain systems
8	Lack of clear legal guidelines and standardized regulations	No clear legal frameworks and standardized regulations to oversee activities pertaining to blockchains

Row	Weakness Title	Brief Description
9	Incompatibility with existing systems and processes	Incompatibility with conventional systems, necessitating large-scale modifications in infrastructure as well as organizational processes.
10	Transaction speed and latency limitations	Slow confirmation of transactions because of consensus mechanisms, as well as small block capacity.
11	Complexity in updating and managing smart contracts	Difficulty in updating smart contracts after their deployment and coding errors risks.
12	Problems with complete transparency without the compromise of confidential content	Difficult trade-off between transparency and confidentiality in blockchain networks.

4-2-2 Cyberattacks and Intrusions into the Blockchain Network

Due to its decentralized nature and use of complex cryptographic techniques, blockchain technology remains one of the most secure methods to store and transfer data. The inherent security that comes with blockchain, however, does not imply complete safety from cyber intrusions, especially considering that blockchain systems are still vulnerable to a number of complex and atypical threats that can threaten the security, operations, and legitimacy of the blockchain system. One of the most notable and prevalent types of attacks is known as the 51% attack, where one or more users gain access to more than fifty percent of the critical mass computing power of the network. The attacker(s) can then reverse valid transactions, verify fraudulent transactions or change the bully chain.

Moreover, attackers may focus on specific network nodes to gain access or interrupt communication amongst the nodes, therefore shutting down the operation of the network. Other significant risks include phishing, social engineering, and other vulnerabilities related to digital wallet and user interface software, which could compromise the security

of the blockchain. Furthermore, smart contracts, by being programmable, could also possibly present flaws that are used by hackers in an effort to penetrate the system. This group of threats requires robust security controls, real-time monitoring, timely and continuous updating of protocols, as well as training of users, in an effort to maintain the most security for blockchain networks and sustain stakeholder interest.

- **Violation of Privacy and Disclosure of Sensitive Data**

Transparency, coupled with the ability of each network member to view each transaction, is one of the inherent characteristics of block-chain technology. The characteristic has several advantages, such as increased trust, correct track-and-trace, and fewer instances of fraud. However, with the advantages, transparency, in this context, becomes the greatest threat to privacy—especially where green supply chains deal with sensitive commercial information, employee, customer, and other stakeholder personal information. Because it is public and unchangeable, once information has been committed to the blockchain, it becomes accessible to anyone with network connections, leaving the risk that trade information, financial data, or contract details will become public. That publicization has the potential to create severe financial losses to organizations and damage their reputation with customers and partners.

In addition, in some jurisdictions, data protection laws establish rigid requirements for protecting personal information, such as the General Data Protection Regulation (GDPR) in the European Union, which cause challenges of compliance for blockchain technology. Thus, with the wish of maintaining the transparency versus privacy balance, advanced encryption technologies, private or permissioned blockchain technologies and smart contracts to apply controlled access to the data are just some of the solutions considered necessary. Also, regulations and internal policies within organizations which provide for data protection also helps maintain the trust of all stakeholders in the supply chain.

- **Risk of Errors or Bugs in Smart Contracts**

Smart contracts represent one of the foundations of blockchain technology, offering the ability to execute contracts automated, secured and without any intermediaries. These contracts are written onto the blockchain in code, and are intended to independently execute exactly what is supposed to happen (such as payment, transfer of ownership, etc.). However, this automation and intelligence also comes with significant technical complexity which can always introduce errors alongside vulnerabilities. The key

issue, however, is that smart contracts are effectively immutable after being put onto the blockchain; if there are bugs, logical mistakes, or security holes in their code, it becomes nearly impossible, or unbelievably difficult, to fix them, often to the tune of major financial consequences, not to mention legal issues too. Hackers can exploit these vulnerabilities, they can result in improper payments, or they can result in locked out assets. Thus, the development of smart contracts is less safe as there are no standardized development processes for building smart contracts and there are no standard testing frameworks for building smart contracts, which means the risk of bugs is elevated. To combat these issues, it is necessary to build appropriate testing procedures into their development, conduct security audits with qualified experts, write the contracts in safer programming languages, and build automated analysis tools to analyze the code for potential vulnerabilities.

- **Instability and Rapid Changes in Blockchain Technology**

Blockchain technology, being one newly emerging technology, has been subject to many changes and advances during the past few years in terms of standards, algorithms, protocols, and development tools. Whilst this rapid change has provided many innovative prospects, it also presents considerable challenges for users and organizations. Technological volatility means that accepted standards and technology today may quickly become obsolete and some new versions or other technology may replace them. This makes it difficult for an organization to make long-term, stable, and strategic plans to deploy the use of blockchain, including ongoing investments in training, updating program software and infrastructures, which are costly and risky. Furthermore, continual changes may cause incompatibility with other software or hardware versions and create supply-chain integration challenges. Additionally, non-standardized and unclear regulation present in most countries exacerbates challenges faced by these changes whilst providing legal ambiguity to users and investors. To counter such challenges, organizations need to develop greater flexibility, pay attention to staff training and empowerment, and participate actively in technology communities in order to work together to harmonize and coordinate standards to permit optimal exploitation of blockchain technology.

- **Lack or Delay in Developing Supportive Laws and Regulations**

One of the most significant barriers to the acceptance and dissemination of the application of blockchain technology continues to be insufficient authoritative legal frameworks and enabling regulations that would allow for its sustainable supply chain applications and its use in many other areas. In most countries, and jurisdictions, however, enforceable legislation regarding issues like ownership and data, security and privacy, liability and dispute resolution relating to blockchain projects have either not been developed or only exist at a draft or incomplete form, placing considerable ambiguity onto users, investors and organizations from incurring potential legal and financial risks. Unclear regulations may limit the use of blockchain, scare investors, and lead to complicated legal disputes. Furthermore, absent enabling legislation the potential for abuse and misuse through blockchain platforms only grows stronger, which jeopardizes public trust in blockchain technology. As a result, developing implementable and up-to-date laws will require input from technical experts, legal experts, lawmakers, and members of the community as it is an urgent need to achieve sustainable premature development in blockchain technology.

- **Opposition or Resistance from Policymakers and Legal Authorities**

Apart from vagueness in clear directives, resistance or pushback from some policymakers and legal enforcement agents can jeopardize the growth of blockchain technology. Resistance occurs principally from incomplete knowledge about the technology, loss of control over information and money movements, among other security and social issues. Some authorities, with the technological advancement and the prospective effect of blockchain on economic, financial, and legal landscapes, would postpone passing relevant laws or even impose prohibitions. The proceedings would create an indeterminate market atmosphere, discourage investment, and slow technological advancement. What's worse, inadequate coordination and convergence between many legal and regulatory authorities would foster confusion as well as incompatible rulings. Overcoming this challenge will require educating and building awareness among policymakers, encouraging professional discourses among various stakeholders, and formulating clear and technologically and economically warranted favorable policies.

- **High Costs of System Maintenance and Upgrades**

Implementing blockchain technology on a large scale, in addition to the initial setup costs, requires significant resources for continuous maintenance, upgrades, and system development. Blockchain technology demands complex hardware and software infrastructure, which increases electricity, equipment, and technical maintenance costs. In addition, because the technology continues to advance rapidly and new procedures must be put into place, the program must be continuously enhanced and brought into compliance with new laws, with the effect that operating costs are always tremendously great. These costs become an important disincentive when small and medium enterprises consider adopting blockchain, but in other cases, it could lead projects to fail. Furthermore, the necessity of qualified staff to administer and maintain systems escalates human resource expenditures. For this reason, proper cost evaluation, adequate financial planning, and implementing cost-efficient business plans are key.

- **Legal Restrictions on the Use of Blockchain Data**

In addition to general legal challenges, some specific constraints in the use, storage, and transferability of information committed to the blockchain potentially could hinder the creation of its applications. Some information safety laws, such as the European Union's General Data Protection Regulation (GDPR), impose rigid requirements with respect to access, modifications, and right to erasure that directly conflict with the nonremovable nature of blockchain data. It presents legal issues that might compel organizations to reassess the nature of their blockchain networks or place limits on their use. Moreover, national and global laws might impose bans upon cross-border transfer of confidential information, where it goes contrary to the decentralized and global nature of blockchain. These legal, regulatory issues not only present technological challenges but also heighten legal and financial risks. In order to counter these challenges, it will be important to create technological solutions like sophisticated encryption, the adoption of private blockchains, and the institution of legal frameworks specific to the nature of blockchain—so that its use cases could mature in an unconditionally secure and legal fashion.

- **Lack of Coordination Among Blockchain Network Stakeholders**

Failing to reach a consensus along the many players in the supply network, is considered one of the most significant challenges faced when considering the use of blockchain technology within sustainable supply chains. Network players have competing

goals, interests, and outlooks need to collaborate with each other, coordinate their efforts and reach goal congruence; not only for the blockchain project itself but within the supply chain. If consensus is lacking across participants in terms of goal congruence, priority congruence, or operating policy, conflict, trust, and willingness to share information in a timely manner will be undermined. The lack of shared criteria or guidelines is likely to entail confusion and associated technical or management issues. Such issues could impede the optimum operation of the supply chain blockchain network with some parties likely to disengage, and hence addressing this issue can only come from establishing its governance framework, making stakeholders aware of its importance, and having regular coordination meetings.

5 Conclusion

In this work, the application of blockchain technology to sustainable supply chains has been extensively analyzed under the framework of strengths, weaknesses, opportunities, and threats analysis (SWOT analysis). The results identified that blockchain has a high capability to increase transparency and accurate tracing of transactions, which can increase trust among members and encourage increased cooperation through the supply chain. Major benefits from this technology are the permanent and indelible registration of information, decentralized structure, elimination of centralized intermediaries, and the potential for automating procedures through smart contracts. In the long term, these characteristics can generate lower costs from operations and increased effectiveness of supply chain systems. Beyond that, increased data availability and coordination from the members of the network, and the capability to generate transparent and accountable systems, are other strengths that enhance the use of blockchain in different domains.

But through these advantages, a number of challenges and weaknesses also emerged, which can hamper the complete and effective application of this technology. Technical challenges and requirement for skilled expertise, absence of advanced infrastructure, high installation costs, and deficiency in skilled human resources are a few most serious technical and organizational challenges. Further technical and structural problems are limitations on scalability and performance, security and privacy, lack of explicit legal architecture and common global standards, speed limitations and latency on transactions, smart contract complexity for administration, and the difficulty in ensuring

transparency without losing sensitive information. These need to be tackled through properly laid and accurate strategies.

From a threat perspective, risks including cyberattacks and network intrusions, violation of privacy, bugs or faults in smart contracts, technological volatility and rapid changes, deficiency or procrastination on supportive regulations, pushback from regulators and decision-makers, system upgrade and maintenance expenses, and legal restrictions on the usage of blockchain data are all possible factors that might influence the viable use of this technology. Further, lack of coordination between and among stakeholders and players on a network, cultural and managerial transformation risks, power centralization risk toward specific nodes on a network, non-existence of worldwide standards, and misuse risk through malicious parties are other serious threats facing blockchain technology when applied to supply chain contexts.

At the same time, significant opportunities abound for blockchain development and use in supply chains, including the growing global demand for transparent and responsible supply chains, growing awareness on the part of consumers of sustainability and product authenticity, increase in international cooperation on emerging technologies, acceleration of digital infrastructure development in emerging markets, increase in government support for innovation and decentralized technologies, emerging investment opportunities for blockchain and logistics, and willingness on the part of leading brands to employ blockchain to attest product quality and authenticity. In addition, development of international standards and protocols, industries' need for precise tools to combat against fraud, smuggling, and insufficient transparency, and applications for blockchain such as environmental tracking, safety, and health, hold numerous opportunities for performance enhancement and innovative applications within supply chains.

Finally, the overall analysis of strengths, weaknesses, opportunities, and threats confirms that the effectiveness of applying blockchain to sustainable supply chains is contingent upon cautious administration of technical, cultural, legal, and economic challenges. Taking advantage of the benefits of this technology is contingent on IT infrastructure development, training specialized human resources, formulating legal systems and international standards, and organizational cultural shift towards accepting innovative changes. Additionally, stakeholder cooperation and policy support are essential factors in the effectiveness of blockchain applications. With the existing

opportunities, focused investment in the development and application of blockchain technology to supply chains can considerably increase transparency, security, and efficiency, leading to sustainable development in this area. It is, therefore, advised that organizational and policymaking levels, based on these findings, create and establish strategic and operative plans that take advantage of the benefits of blockchain technology.

Future Research Directions

To learn more about how to best use blockchain to help supply chains be better and more eco-friendly, work on future research should be done that focuses on the following:

- Test how well blockchain works in many different businesses by doing case studies and other operations research. This would help people better know how much using blockchain helps in farming, medicine, auto making, and food.
- Study the making of hybrid tech models. People should also work on the making of new tech that mixes blockchain with other new tech. This includes the Internet of Things, computers that use AI, and Big Data. These hybrid models would help supply chains be smarter and work in a more automatic way.
- Do an analysis of new risks and dangers. People should look more into what new security, legal, and admin risks and dangers may come from developing blockchain. They should make suggestions about how to prevent these dangers from happening.
- Study how blockchain can be made to work on a bigger scale. They should do work to find ways to make blockchain work on a bigger scale and to have fewer limits on how fast transactions are done and the money spent. This is more important for projects that are very big and have to be used all over the world.
- Study how much people and groups use technology. They should look into how much humans, cultures, and groups use blockchain and how they use it well. Doing this would help make plans for changing when it is needed.

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