Developing a Blockchain Based Supply Chain CO_2 Footprint Tracking Framework Enabled by IoT

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***Abstract*—In various industries, the convergence of the Internet of Things (IoT) and blockchain technologies has left an indelible mark on the pursuit of decarbonization. These innovations have seamlessly integrated into diverse fields, from manufacturing to logistics, offering sustainable solutions that enhance operational efficiency, transparency, and accountability. The interplay between IoT and blockchain has particularly contributed to the reduction of carbon footprints, fostering environmentally responsible practices. As industries embrace these technologies, the decentralized and transparent nature of blockchain ensures traceability in supply chains, while IoT devices facilitate real-time data monitoring. Together, they create a powerful synergy that not only streamlines processes but also drives a collective commitment to reducing environmental impact, marking a paradigm shift towards greener and more sustainable industries. Within this landscape, this research offers a comprehensive exploration of the transformative potential of blockchain in supply chain management, emphasizing its intricate connection with IoT and carbon footprint reduction. The conceptual model presented delineates the seamless integration of these elements, providing a nuanced understanding of how blockchain can revolutionize transparency and sustainability. Through practical examples and a layered diagram, it showcases the tangible benefits of this integration, highlighting its capacity to enhance data integrity and transparency in real-world supply chain scenarios. The research stands as a testament to the instrumental role that blockchain can play in fostering environmentally responsible practices within supply chains, laying the groundwork for a more sustainable future.**

***Keywords*—Blockchain; IoT; supply chain; carbon footprint; sustainability**

I. INTRODUCTION

The management and reduction of CO_2 emissions present a multifaceted challenge for organizations, as they grapple with diverse emission sources and the urgency of climate change mitigation [1]. Tracking CO_2 emissions across the entirety of the supply chain introduces complexity due to the global nature of supply networks, encompassing numerous suppliers and intricate logistics networks [2]. Ensuring accuracy, consistency and transparent emissions data throughout the supply chain is a formidable task, complicated by variations in reporting methodologies, data availability, and the reluctance of some stakeholders to disclose emissions information. Also, how IoT devices can communicate directly through autonomous data will be challenging because the reports and data are usually ready to use [1].

In an era of escalating environmental concerns, the logistics industry stands at the forefront of innovation, striving to reduce its carbon footprint and enhance its overall sustainability [3]. The convergence of emerging technologies, such as blockchain and the Internet of Things (IoT), holds immense promise in transforming logistics operations towards greener and more efficient practices [4], [5]. This deductive research proposal outlines an extensive investigation into the economic and environmental benefits of utilizing blockchain for managing and optimizing green logistics processes, as well as the pivotal role that blockchain plays in verifying the authenticity and accuracy of sustainability claims and certifications within the logistics industry [6]. The Internet of Things (IoT) also emerged as a powerful tool that promises not only to revolutionize the way logistics operations are managed but also to substantively contribute to global sustainability goals [7], [8].

This research is anchored by three central research questions. First, aims to elucidate the economic and environmental benefits brought about by the incorporation of blockchain technology into green logistics processes. Second, it delves into the role of blockchain in validating sustainability claims and certifications within the logistics industry, while concurrently examining the autonomous data generation capabilities of IoT devices. Lastly, it explores the mechanisms and technologies that facilitate autonomous data generation by IoT devices to support field devices in logistics operations. These questions provide the guiding framework for our research inquiry.

The initial theory posits that the integration of blockchain technology, in conjunction with the utilization of the Internet of Things (IoT), has the potential to revolutionize the green logistics industry by offering solutions to key challenges. This theory is founded on the premise that blockchain can enhance transparency, reduce costs, and improve the accuracy of sustainability claims within the logistics sector. Additionally, IoT technologies, when harnessed effectively, can autonomously generate and share data, thereby optimizing field devices' operation and decision-making processes. It is hypothesized that the synergy between blockchain and IoT, it is hypothesized, can lead to substantial economic and environmental benefits for organizations engaged in green logistics operations. Through rigorous research and analysis, the paper seeks to validate and refine this initial theory, offering valuable insights into sustainable business practices in the context of logistics and environmental responsibility.

To provide a clear roadmap for the subsequent sections of this research paper [9], it commences with an extensive review of existing literature, establishing the theoretical foundations of the study. Following that, the research methodology will be delineated, elucidating the processes of data collection, analysis, and interpretation. Mixed methodologies such as rigorous literature reviews, incisive case studies, targeted surveys, and collaborative research will be used. Subsequently, the research presents findings, addressing each research question individually [10]. Finally, it will be concluded with a comprehensive discussion, drawing connections between the research outcomes and their broader implications for green logistics, blockchain technology, and IoT applications.

II. Literature Review

A. Green Logistics

Green logistics, often referred to as environmentally sustainable logistics or eco-logistics, in the field of logistics and supply chain management, green logistics has become a crucial concept due to the rising challenges of environmental sustainability [10]. In the past, the logistics industry mainly concentrated on making operations more efficient and economical, sometimes neglecting environmental concerns. Nevertheless, as environmental problems like climate change and resource depletion became more important, there was a significant change in how logistics was perceived and carried out [11], [12].

Green logistics is a major change in how we do logistics. It's all about making sure that by moving things around, it doesn't harm the environment. This means doing things like minimizing pollution, using less energy, and not making as much waste. At the same time, it still be wanted to use resources wisely and make money [13]. This change shows that now logistics should be considered as a way to help the planet and make money, and there is a need to think about both things as the world changes.

B. Blockchain Technology

Blockchain Technology can be defined as a distributed and digital ledger technology that transparently records and verifies every step in the supply chain [14]. It offers a secure and immutable record-keeping system that enables real-time tracking of environmentally friendly practices, facilitates transparency in sustainability reporting, and helps organizations make informed decisions to minimize their carbon footprint and enhance ecological responsibility throughout their logistics operations [15]. Blockchain technology offers innovative solutions for reducing carbon footprints and fostering sustainability within supply chains. By providing end-to-end traceability and transparency, blockchain enables companies to pinpoint inefficiencies, optimize transportation routes, and select environmentally responsible suppliers [16]. Smart contracts automate eco-friendly actions, such as choosing energy-efficient shipping options [17]. The immutability of blockchain data ensures the accuracy of emissions records, preventing fraudulent sustainability claims [18]. Decentralization reduces intermediaries, cutting emissions associated with unnecessary transportation [19]. These blockchain-driven solutions empower organizations to simultaneously reduce their carbon footprint and bolster supply chain efficiency and sustainability, aligning business goals with environmental responsibility [20].

C. Literature Gap Analysis

1) Blockchain based sustainable models/applications. The pursuit of sustainable models underpinned by blockchain technology presents a transformative opportunity, particularly when coupled with the integration of IoT autonomous data. Within this context, one promising model is the "Smart contracts and emission token system" [17]. A blockchain-based sustainable model that combines smart contracts and emission tokens can significantly enhance sustainability efforts by providing a transparent, automated, and secure framework for tracking, verifying, and incentivizing emissions reductions [21].

In this innovative model for combating climate change and promoting sustainability, emissions are transformed into digital tokens, symbolizing the reduction or removal of greenhouse gases from the environment [22]. These tokens are generated based on scientifically validated emission reduction projects or actions. Crucial to this system are smart contracts, which lay out the terms and conditions of these emission reduction initiatives, specifying emission reduction goals, the methods for verification, and the issuance of emission tokens upon achieving these goals [23].

By combining smart contracts with emission tokens on a blockchain-based platform, this sustainable model enhances transparency, security, and automation in emissions tracking and reduction efforts [24]. It also encourages organizations and individuals to actively participate in sustainable practices and carbon offsetting while contributing to the global fight against climate change [25].

2) IoT and autonomous data integration with blockchain. A major change in the landscape of sustainable logistics is being brought about by the convergence of IoT, autonomous data generation, and blockchain integration [26]. The diverse potential of these technologies in solving operational and environmental concerns within supply chains has recently been highlighted.

Smart sensors used in the IoT for real-time monitoring have become popular because of their capacity to increase efficiency and transparency [27]. These strategically positioned sensors provide ongoing information on environmental conditions, safeguarding the integrity of goods and materials. Vehicle performance sensors, for instance, improve fleet management and lower carbon emissions. IoT devices, equipped with sensors and connected to networks, autonomously collect and transmit data in real-time [28]. These devices are capable of capturing environmental variables, vehicle performance metrics, and supply chain data, among others. Their ability to transmit data without manual intervention is a foundational component in achieving autonomous data communication.

Decentralized networks like blockchain play a vital role in enabling IoT devices to communicate autonomously. These networks, often peer-to-peer in nature, facilitate direct data exchange between devices [29], [30]. This eliminates the need for intermediaries and central authorities, streamlining communication while enhancing security and efficiency also, IoT device-generated autonomous data enables data-driven decision-making for logistics operations via direct communication, the optimization of routes and predictive maintenance.

These developments are enhanced by blockchain technology, which offers a transparent and unchangeable ledger for storing data and autonomous data communication generated by IoT devices. It serves as a distributed ledger where data is securely recorded, and time stamped. This ensures data integrity and authenticity, crucial in green logistics, particularly when validating sustainability claims or ensuring compliance with environmental regulations [26]. By guaranteeing the validity of environmental data, this integration strengthens the plausibility of sustainability claims and avoids "greenwashing" [31]. The result of literature study based on the defined themes is discussed in Table I.

TABLE I. LITERATURE STUDY BASED ON THE MAIN THEMES

Research Studies	**Green logistics**	**Blockchain Technology application**	**IoT and autonomous interactions**
Liu and Ma [28]	New energy-saving transportation methods.		IoT application to guide warehousing operations to improve work efficiency.
Rosado Da Cruz et al. [21]	Tracing carbon footprints.	Blockchain technology for monitoring, tracking and tracing the carbon footprints of products. Smart contracts implementation.	
Tan et al. [15]	Green logistics is based on blockchain by integrating IoT and big data in logistics industry.	Applications of blockchain in logistics operations. Transforming traditional operations into blockchain based operations.	
Feroz et al. [18]	Minimizing the CO_2 emission and managing energy.	Blockchain provides prominent levels of privacy, security and traceability.	
Chelh and Ababou [32]		Potential to revolutionize supply chain management by reducing risks like fraud and data breaches while creating a resilient in green supply chain.	
Cruz [26]		Convergence of IoT-Block chain models to enhance data privacy.	
Nizetic et al. [33]			Using IoT devices to simplify process and to have efficiency, sustainability, and quality.
Ahmad [34]		Combining IoT devices and blockchain technology on Ethereum to enable secure, decentralized data exchange and automation with smart contracts in a P2P network, brings transparency.	
This research	Measuring, evaluation, and controlling of CO_2 footprint through supply chain material operations.	Application of blockchain for transparency of material data flow.	Autonomous data communication and interoperability, data privacy and security, connectivity and standardization, data driven decision making with IoT analytics.

The existing literature highlights the potential of integrating IoT autonomous data collection with blockchain technology to create sustainable and transparent supply chains. However, a significant research gap exists in the development and validation of comprehensive models and applications that can be readily adopted by organizations. These models should effectively integrate IoT autonomous data with blockchain, ensuring data accuracy, transparency, and trust throughout the supply chain [32]. To address this gap, the research will focus on bridging the divide between theory and practical application, providing adaptable, user-friendly frameworks for organizations looking to leverage IoT and blockchain for sustainable, environmentally friendly and transparent supply chains [33].

III. PROPOSED SOLUTION

The development of the frameworks should be the primary focus of this research to ensure that the promise of IoT, autonomous data, and blockchain integration is fully realized in sustainable logistics, with substantial advantages for both businesses and the environment. Fig. 1 demonstrates the conceptual model of such framework.

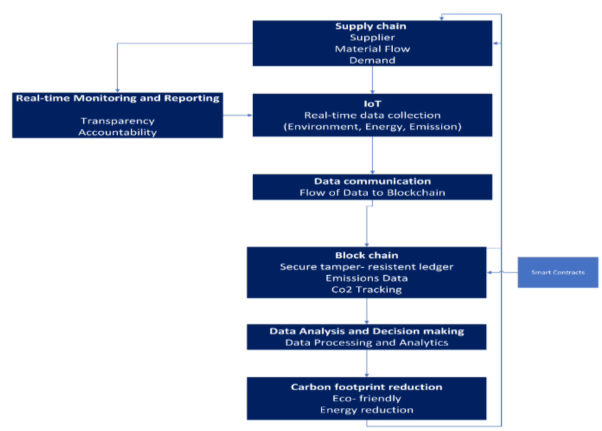

Fig. 1. Illustration of IoT, blockchain conceptual model for reducing overall CO_2 in supply chain.

A. *Supply Chain Layer*

The Supply Chain Layer consists of suppliers, demand and material flow. It ensures efficient sourcing, monitors material movement and forecasts demand, to enhance overall supply chain performance and sustainability [18]. This layer plays a pivotal role in leveraging insights for informed decision-making [34].

B. Real-Time Monitoring and Reporting Layer

Throughout the process, real-time monitoring and reporting are facilitated by this layer. Stakeholders have access to emissions data, ensuring transparency and accountability [35].

C. IoT Layer

In the next layer, IoT devices are deployed throughout the supply chain. These devices autonomously collect real-time data with RFID or NFC communication methods on environmental conditions, energy consumption, and emissions [3].

D. Data Communication Layer

The data collected by IoT devices is transmitted to the Data Communication Layer. This layer manages the flow of data from the IoT devices to the blockchain [33].

E. Blockchain Layer

The data will be received and processed within the blockchain layer. The blockchain acts as a secure and tamper-resistant ledger, recording and time stamping all emissions data. Smart contracts, self-executing pieces of code on the blockchain, enforce predefined rules and automate processes. In supply chain and sustainability, smart contracts can execute actions based on the received data, such as verifying emissions compliance or triggering alerts for specific thresholds. On the other side, Emission tokens quantify a certain amount of carbon footprint emissions associated with a specific activity, process, or entity [36]. These tokens are part of the broader concept of carbon credits or carbon offset mechanisms, where organizations seek to compensate for their carbon emissions by investing in projects that reduce or capture an equivalent amount of greenhouse gases elsewhere. Emission tokens often leverage blockchain technology, providing a transparent and immutable ledger to track the generation, transfer, and retirement of these tokens. Blockchain enhances the integrity and traceability of carbon-related data [37].

F. Data Analysis and Decision Layer

The processed data is then sent to the Data Analysis and Decision Layer. Here, data analytics tools are used to gain insights into emissions patterns and identify opportunities for reducing carbon footprints [38].

G. Carbon Footprint Reduction Layer

The insights and recommendations from the Data Analysis and Decision Layer inform the actions taken in the Carbon Footprint Reduction Layer. These actions can include selecting eco-friendly transportation methods, reducing energy consumption, or adjusting sourcing practices [39].

IV. EVALUATION

A. Validation Model

The validation of this research asserts the robustness and credibility of the proposed model, affirming the veracity of our claims. The focus will be mainly on the order and transport transactions as can be seen in Fig. 2.

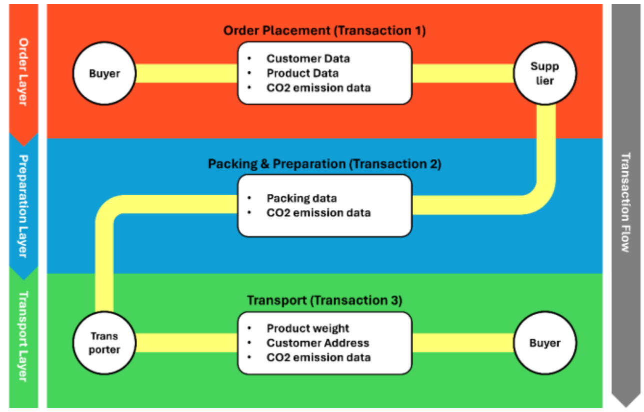

Fig. 2. Transaction and data flow of validation model for the proposed solution.

1) Order placement (Transaction 1). The initial transaction occurs when the buyer (which could be a distributor, retailer, or end consumer) places an order with the supplier. This transaction involves the transfer of order details, quantities, and specifications.

2) Packing and preparation (Transaction 2). The supplier initiates a transaction related to packing and preparing the goods for shipment. This may include generating packing lists, labeling, and preparing documentation.

3) Transport (Transaction 3). When the goods are ready for shipment, the supplier initiates a transaction to notify the transportation entity or logistics provider. This transaction includes information about the shipment, such as weight, dimensions, and the destination.

This approach has several advantages:

- Interoperability. Utilizing a general blockchain provides the advantage of fostering compatibility with diverse blockchain networks. This approach facilitates interoperability with other systems and applications that conform to prevalent blockchain standards.
- Ease of Integration. General blockchains typically feature well-established APIs and tools for network interaction. This simplifies the integration process, enabling concentration on the particular data intended to be stored in the blockchain, rather than navigating the intricacies of blockchain development.
- Security and Immutability. Leveraging an existing blockchain network assures the inherent security and immutability characteristics within blockchain technology. The decentralized and tamper-resistant nature of the blockchain ensures the integrity of the embedded information.
- Cost Efficiency. Opting for an existing blockchain network proves to be a more cost-effective choice. Creating a dedicated blockchain network can be resource-intensive, making the utilization of an established network a pragmatic alternative.

Overall, this approach not only simplifies the development process but also leverages the strengths of blockchain technology without the need for extensive customization. It allows us to focus on the specific data and use case while benefiting from the broader blockchain ecosystem.

B. Results

The study yields a basic yet instructive blockchain implementation tailored to a supply chain context. Example transactions, such as order placement, packing, and transport, are utilized to showcase how data is structured within blocks and how blocks are sequentially linked. The creation of a genesis block and the utilization of cryptographic hashing underscore the foundational principles of blockchain technology.

The code serves as a steppingstone for comprehending more intricate blockchain frameworks and their real-world applications and highlights the importance of data integrity, decentralization, transaction transparency and key attributes of blockchain technology that contribute to its potential in optimizing supply chain management.

V. Conclusion

In this comprehensive exploration of blockchain integration in supply chain management, it is navigated through fundamental concepts and practical implementations, offering a nuanced understanding of the transformative potential of blockchain technology. The discussion commenced with the delineation of a conceptual model intricately weaving together the realms of the Internet of Things (IoT), blockchain, and carbon footprint reduction. The layers, ranging from IoT data collection to carbon footprint reduction strategies, provided a holistic perspective on how blockchain could revolutionize transparency, traceability, and sustainability within supply chain operations.

The ensuing creation and visualization of a layered diagram reinforced the intricate connections between IoT-enabled data acquisition, secure transmission through blockchain, data analysis for informed decision-making, and the imperative action layer focused on carbon footprint reduction. This conceptual model stands as a testament to the nuanced orchestration required to imbue supply chains with efficiency, accountability, and environmental responsibility. The focus on a supply chain scenario with example transactions elucidated the potential for blockchain to enhance data integrity and transparency in real-world applications. Encryption of blockchain data stands out as a crucial avenue for future research studies. Exploring robust encryption methods to restrict outsider access ensures that sensitive supply chain information remains secure and confidential. This avenue addresses growing concerns regarding data privacy and confidentiality within blockchain networks.

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