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Blockchains for industrial Internet of Things in sustainable supply chain management of industry 4.0, a review

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ABSTRACT

The integration of blockchain technology in the Industrial Internet of Things (IIoT) for sustainable supply chain management in the context of Industry 4.0 offers several potential benefits. A public and auditable record of the environmental impact of each supply chain stage can be made using blockchain technology. A more streamlined and effective supply chain is made possible by blockchain's decentralized structure. Delays, mistakes, and the need for middlemen are decreased by real-time access to a shared ledger. IIoT devices like sensors and RFID tags can provide real-time data on the location, condition, and environmental parameters of goods. Blockchain can then be used to record and incentivize sustainable practices, such as reducing energy consumption or minimizing waste. The integration of blockchain with IIoT can develop the supply chain management for enabling real-time tracking of goods, optimizing inventory management, and ensuring compliance with sustainability standards. The paper provides a comprehensive overview of the key challenges facing traditional supply chains and how the combined use of Blockchains and IIoT technologies. The review also evaluates the environmental, social, and economic implications of adopting Blockchain-enabled IIoT solutions in supply chain operations. Furthermore, the review assesses the current state of research and development, identifying gaps in existing literature and proposing avenues for future exploration. As a results, by highlighting the synergies between these technologies, it seeks to inspire further innovation and adoption, ultimately fostering a more resilient, transparent, and environmentally conscious industrial ecosystem.

1. Introduction

The fourth industrial revolution, characterized by the incorporation of automation, digital technology, and data interchange in production environments, is referred to as "industry 4.0". It is characterized by the use of cutting-edge technologies, including automation, artificial intelligence, the Internet of Things, and data analytics, to enhance processes in industry and manufacturing. Blockchains are distributed, decentralized digital ledgers that safely log transactions via a computer network. Every transaction is kept in a block, which is then connected to other blocks to build a chain. The term Industrial Internet of Things (IIoT) describes how industrial machinery and processes are integrated with sensors, software, and other technology. IIoT makes data gathering and sharing possible, enhancing industry productivity and decision-making. Integrating socially and ecologically conscious practices into the supply chain is a key component of sustainable supply chain management. It seeks to guarantee moral behavior along the whole supply chain and reduce the negative effects on the environment.

Within the framework of Industry 4.0, a prospective use of blockchain technology and the Industrial Internet of Things (IIoT) is sustainable supply chain management [1]. Because blockchain technology offers transparency, efficiency, and security along the whole supply chain, its integration with the Industrial Internet of Things for sustainable supply chain management is consistent with Industry 4.0 concepts. This has the potential to support more ethical and sustainable business practices across a range of industries. In order to support sustainability goals, this combination can improve supply chain processes' efficiency, security, traceability, and transparency. This entails taking into account social, economic, and environmental aspects while incorporating sustainable practices into the supply chain. Fig. 1 illustrates

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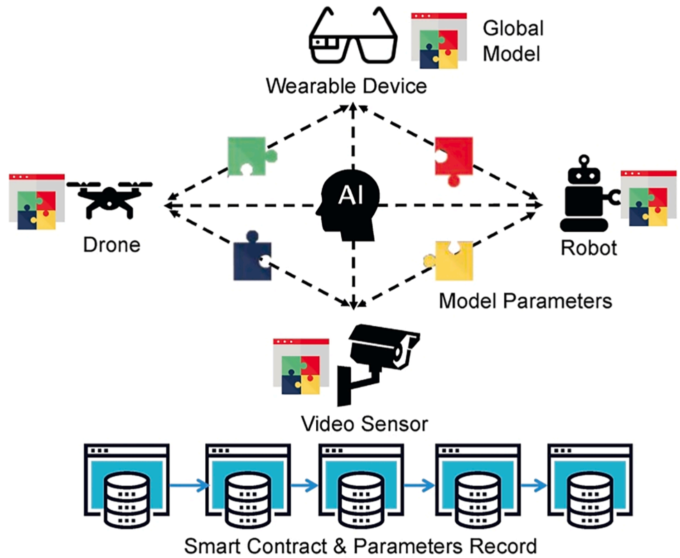

Fig. 1. Artificial intelligence (AI) for the Internet of Things (IoT) based on blockchain technology [2].

blockchain-based artificial intelligence (AI) for the Internet of Things (IoT) [2].

IIoT sensors are able to gather information on emissions, energy usage, and other environmental aspects. By integrating this data with blockchain, companies can track and verify their sustainability efforts, ensuring adherence to environmental standards. IIoT devices foster collaboration by providing real-time data to all participants. For example, manufacturers, suppliers, and logistics providers can access a shared platform built on blockchain and IIoT for seamless collaboration and information exchange. Blockchain technology offers an unchangeable, transparent record of transactions. This transparency may be expanded to include the whole supply chain, giving interested parties the ability to follow a product's path from production to delivery [3]. Additionally, Blockchain offers a secure and decentralized ledger that makes data storage transparent and immune to alteration conceivable. A safe and verifiable information chain is created by including a timestamp and a link to the preceding block in each chain [4]. Furthermore, Blockchain makes it possible for pertinent supply chain parties to share this data securely and instantly. This improves the ability to collaborate and make decisions [5].

Implementing blockchain for IIoT in sustainable supply chain management aligns with the broader goals of Industry 4.0 by creating a more connected, efficient, and environmentally conscious industrial ecosystem. However, it's essential to carefully consider factors such as scalability, interoperability, and industry-specific requirements when deploying such solutions [6]. Secure data of industrial internet of things in a cement factory based on a blockchain technology is shown in the Fig. 2 [7].

Real-time information on the position and condition of items, supplies, and assets along the supply chain is provided via IIoT sensors and equipment. So, enhanced visibility allows for better monitoring of resources, reducing waste and improving overall efficiency [8]. The continuous stream of data from IIoT devices enables data-driven decision-making processes. In order to improve decision-making, predict disruptions, and optimize supply chain operations, analytics and machine learning algorithms can be applied to this data [9]. Additionally, by continuously monitoring the state of machinery and equipment, the IIoT makes predictive maintenance easier. This prolongs the life of assets, cuts down on downtime, and avoids expensive breakdowns [10].

The term "conversational AI" describes the application of machine learning, natural language processing, and artificial intelligence to create conversational interfaces that resemble those of humans. Through the use of these technologies, computers can now comprehend human input and react to it in a way that is more instinctive and natural [11]. Also, blockchain technology can be utilized to track the source of raw materials in the fashion industry. For instance, companies like Provenance are using blockchain to ensure that the cotton used in garments is sourced from farms that adhere to sustainable agricultural practices. Also, blockchain can support recycling programs by creating transparent and traceable systems for waste management. The Plastic Bank, for instance, leverages blockchain to provide incentives for recycling plastic waste. It can also be used to certify fair trade practices in the coffee industry. Companies like Bext360 use blockchain to track coffee beans from the farmer to the retailer, ensuring that farmers are paid fair wages. Moreover, blockchain can facilitate the tracking and trading of carbon credits. Companies can earn carbon credits by reducing their emissions,

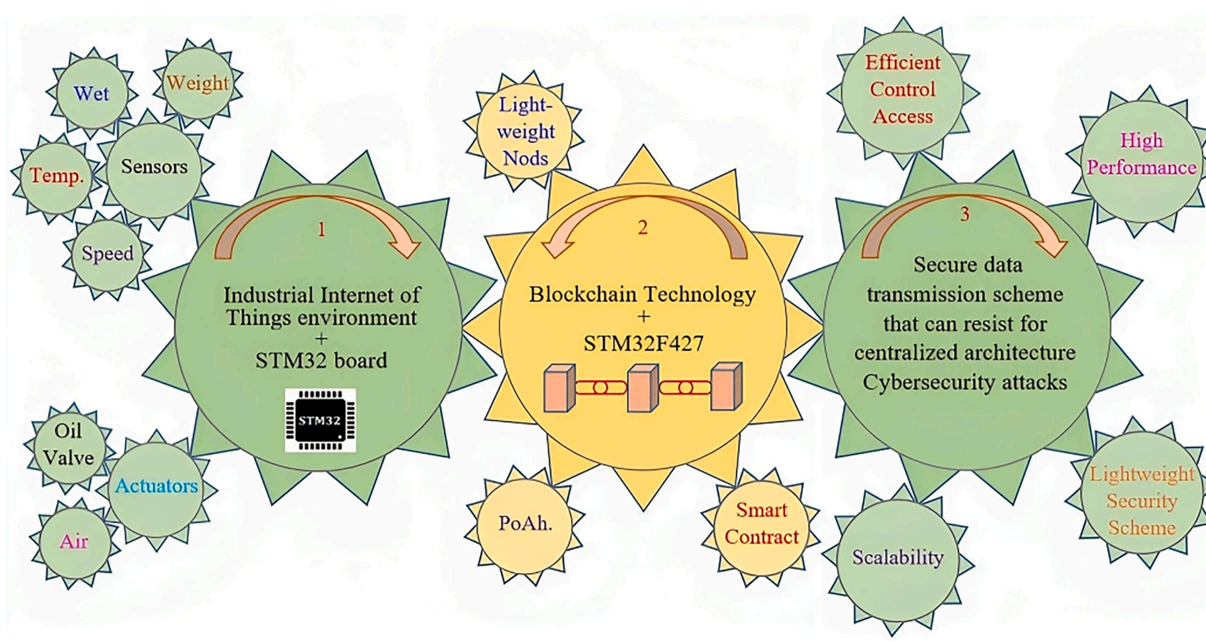

Fig. 2. Blockchain-based secure industrial internet of things data in a cement mill [7].

which are then recorded on a blockchain. These credits can be traded on a blockchain platform to offset emissions.

To enhance quality of machined parts in drilling operations of composite materials, a research work is presented by Ge et al. [12]. To enhance sustainability in drilling operations of thermoplastic parts, optimized machining parameters are obtained by Ge et al. [13]. To enhance productivity in manufacturing process of reinforced thermoplastic polymer, a review is presented by Ge et al. [14]. To increase performance of manufactured parts from carbon fibre reinforced thermoplastic, simulation and experimental study of different damages is presented by Ge et al. [15]. To increase performances of part production using composite materials, thermal analysis during drilling operations of thermoplastic materials is presented by Ge et al. [16]. A comparative study of conventional drilling operations is investigated by Ge et al. [17] to increase fatigue life of machined parts.

Karimi Ghaleh Jough and Şensoy [18] developed meta-heuristic techniques to enhance risk management in concrete moment frames by estimating the bursting risk of mid-rise steel tension frame structures.

Using the FCM-PSO Method, Karimi Ghaleh Jough and Şensoy [19] investigated Steel Moment-Resisting Frame Dependability by Interval Analysis in order to decrease execution time and increase accuracy while estimating siesmic fragility curves. Using finite element simulations, Karimi Ghaleh Jough and Golhashem [20] examined the out-of-plane motion of informal brick constructions, the self-weight axial deformation of walls constructed using the lightest masonry materials available today was decreased. Karimi Ghaleh Jough and Beheshti Aval [21] employed the fuzzy C-means algorithm-based adaptive neuro-fuzzy inference framework to build an SMRF structure's seismic susceptibility curve. This allowed for the incorporation of epistemic uncertainty and increased computation accuracy. Ghasemzadeh et al. [22] examined the aspects that define and place infrastructure projects in context in order to point out and illustrate the present shortcomings of using BIM for infrastructure projects. The unpredictability of epistemic knowledge using a group-based data processing method in contrast to the previously outlined techniques, Karimi Ghaleh Jough et al. [23] implemented vulnerability in order to keep the same computation time while increasing power and output precision along with accuracy. Karimi Ghaleh Jough and Ghasemzadeh [24] presented the unknown interval assessment of steel the moment the framework by building of 3d-fragility curvature towards optimized fuzzy methods investigation, which aimed to improve precision and reduce execution time during driving the 3d-fragility curvature.

Karimi Ghaleh Jough [25] looks at how steel wallposts affect not structural concrete walls' out-of-plane action in attempt to produce wallposts for masonry walls with lower adjustment elements. To decrease the envirmental pollution during manducating process, sustainable CNC machining operations is studied by Soori et al. [26]. Soori and Karimi Ghaleh Jough [27] evaluate the use of artificial intelligence in the optimization of steel moment frame structures in order to improve the performance of these structures under operating conditions. Karimi Ghaleh Jough and Ghasemzadeh [28] have created SMRF reliability prediction based on the combination of neural network and incremental dynamic analysis, with the goal of improving performances by reducing random uncertainty in steel structures. Soori et al. [29] evaluated uses of smart robotics systems to improve productivity in industry 4.0. Prediction of seismic collapse risk in steel moment framed structures by metaheuristic algorithm is implemented by Karimi Ghaleh Jough [29]to enhance the performances of steel moment framed structures.

Soori et al. [30-34] suggested virtual machining techniques to evaluate and enhance CNC machining in virtual environments. Soori et al. [35] provided an overview of recent advancements in friction stir welding techniques in order to analyze and improve performance in the component production process using welding processes. Soori and Asamel [36] investigated the use of virtual machining technology to reduce residual stress and displacement inaccuracy during five-axis milling operations for turbine blades. Soori and Asmael [37] investigated possibilities of virtualized machining methods to monitor and lower the cutting temperature while milling things that are challenging to cut. Soori et al. [38] suggested the implementation of a sophisticated virtual machining technique to enhance surface properties during turbine blade five-axis milling operations. Soori and Asmael [39] developed virtual milling procedures to lower dislocation error in impeller blade five-axis milling operations. Soori [40] presented virtual invention as an attempt to study and enhance the process of part production in virtual settings. To analyze and minimize residual stress and surface roughness during EDM machining operations, optimized machining parameters is obtained by Soori and Karimi Ghaleh Jough [41].

Soori and Asmael [42] Presented a summary of recent developments from literature to evaluate and improve the parameter approach for optimization of machining processes. To enhance energy consumption efficiency, data availability and quality throughout the supply chain, and component manufacturing precision and reliability, Dastres et al. [43] proposed a review of RFID-based wireless manufacturing systems. Soori et al. [44] explored the potential benefits of machine learning and artificial intelligence for CNC machine tools in order to increase profitability as well as efficiency in the element production sector. In order to enhance the functionality of machined parts, Soori and Arezoo [45] investigated the issue of measuring and reducing residual stress during machining processes. In order to improve the integrity of the surface and minimize residual stress throughout Inconel 718 grinding, Soori and Arezoo [46] suggested using the Taguchi optimization method to figure out the best machining parameters. To prolong the life of the cutters used in machining processes, Soori and Arezoo [47] investigated various approaches for tool wear prediction algorithms. Soori and Asmael [48] examined the use of computer-assisted process planning to increase efficiency of component manufacturing methodologies. Dastres and Soori [49] investigated how to enhance decision-making through the use of web-based advancements in decision-support technologies to provide data storage and management options.

Dastres and Soori [50] studied applications of artificial neural networks to look at ways to put them into practice to improve product efficacy. Dastres and Soori [51] recommended utilizing communication platforms in environmental concerns to lessen the negative effects of technological advancement on calamities. To improve the internet security of networks and data, Dastres and Soori [52] suggested the secure socket layer.

Dastres and Soori [53] evaluated and suggested the gaps between suggested ways in order to create the decision support systems methodology by studying the advancements in web-based decision support systems. The most recent advancements in network threats were reviewed by

Dastres and Soori [54] in order to enhance network security methods. Dastres and Soori [55] looked at image processing and analysis systems to increase their potential for a range of uses. Soori and Arezoo [56] have made modifications to tool deflection, geometrical, dimensional, and thermal flaws to increase the accuracy of 5-axis CNC milling procedures. Soori et al. [57] review recent advances in published publications to assess and improve the impacts of artificial intelligence, machine learning, and deep learning on advanced robotics.

To find out if the cutting parameters affect the tool life and cutting temperature during milling operations, Soori and Arezoo [58] developed a virtual machining system application. Soori and Arezoo [59] examined the effects of coolant on the cutting the outside temperature, tool utilize, and roughness of the surface during the turning of Ti6Al4V material. A review of recent advances from published publications is conducted by Soori [60] in order to investigate and modify composite constructions and materials. Soori et al. [61] explored methods to increase industry quality control and optimize part production processes. 4.0 smart factories with the application of IoT. In order to lessen the amount of damage that occurs on drilling instruments, Soori and Arezoo [62] proposed a virtual machining. Soori and Arezoo [63] decreased roughness of the surface and residual stress to improve the total quality of the product created by abrasive water jet cutting. To increase the accuracy of turbine five-axis milling operations of turbine blades, Soori [64] determines and adjusts potential deformation inaccuracies. In order to evaluate and enhance the accuracy of CNC machining processes and components, Soori and Arezoo [65] investigated the use of the finite element technique in CNC machine tool modification. To evaluate and optimize industrial robot energy use. Soori et al. [66] investigated a number of energy use optimization strategies.

Soori et al. [67] conducted a study to evaluate and enhance the component production process in Industry 4.0 by analyzing the advantages and disadvantages of virtual manufacturing systems. Soori et al. [68] are studying artificial neural networks to create supply chain management in advanced manufacturing. In order to improve the battery management of upcoming electric aircrafts, Raoofi and Yildiz [69] studied battery state estimate methodologies employing machine learning for battery management systems of aircraft propulsion batteries. Raoofi and Yasar [70] analyze the frontier digital technologies in continuing airworthiness management frameworks and applications to highlight the untapped potential for digital transformation in aircraft maintenance and to elucidate the current relationship between the digital world and maintenance practices.

This study adds to the growing conversation on how blockchain technology and the Internet of things will revolutionize sustainable supply chain management in the context of the industry 4.0 paradigm. It examines how improved traceability and accountability could minimize carbon footprints, maximize resource use, and encourage moral behavior. An introduction to Industry 4.0 and its critical role in influencing the direction of industrial processes is given at the outset. The article discusses the incorporation of IIoT technologies into supply chain operations and explains how they may improve efficiency, visibility, and traceability.

There is no review paper on the broader Industry 4.0 framework, which includes Blockchains for industrial internet of things, automation, data exchange, and smart manufacturing technologies by emphasize the role of blockchain in enhancing sustainability within supply chains management. Also, the integration of blockchain with Industrial Internet of Things (IIoT) within the context of sustainable supply chain management are not fully explored in previous review papers. The review emphasizes sustainable supply chain management, detailing how blockchain technology can reduce carbon footprints, enhance resource efficiency, and promote circular economy principles. The paper also situates the discussion within the Industry 4.0 paradigm, highlighting how blockchain and IIoT contribute to the smart factory concept, real-time data analytics, and automated decision-making processes.

The review's main objective is to demonstrate how Blockchains may be used as a strong basis for protecting and improving IIoT-enabled supply chains. The intrinsic properties of blockchains—transparency, immutability, and decentralization—are examined in relation to how they might be able to help with supply chain sustainability issues. The analysis of smart contracts, consensus techniques, and interoperability features yields a thorough comprehension of the underlying technology. The article also looks at pilot projects and real-world case studies where Blockchains and IIoT have been effectively used in Industry 4.0 supply chain contexts. These examples highlight the advantages, difficulties, and practical ramifications of putting this integrated framework into practice. Consequently, the amalgamation of current knowledge aids scholars, professionals, and decision-makers in using the joint capabilities of Blockchain technology and the Internet of Things to promote sustainable supply chain management in the dynamic context of Industry 4.0.

2. Transparent and traceable supply chain

A transparent and impenetrable ledger is offered by blockchain. The blockchain enables the recording of every event or transaction in the supply chain, resulting in an auditable and unchangeable history. Stakeholders can track a product's origin and path across the whole supply chain with blockchain technology [71]. This is especially helpful for sectors of the economy where compliance and sustainability depend heavily on the source of components and materials. Because of blockchain's immutability, a transaction cannot be changed once it is recorded. This feature makes it easier to stop fraud and counterfeiting in the supply chain since it makes it instantly obvious when someone tries to tamper with the data [72]. Blockchain secures transactions via cryptographic methods. By safeguarding data integrity and making sure that only authorized parties can access critical information, this improves the supply chain's overall security [73]. Here's how blockchains are utilized in creating transparent and traceable supply chains within the framework of Industry 4.0:

1. Decentralized and Immutable Ledger: Blockchain offers an unchanging, decentralised ledger for storing transactions across a computer connection. This guarantees that information cannot be changed or tampered with after it has been recorded. Participants' trust is strengthened by this transparency and immutability in the context of supply chain management [74].
2. Smart Contracts: The terms of the contract are expressly incorporated into the code of smart contracts, also known as self-executing contracts. Automation and enforcement of agreements between supply chain management parties, such as payment terms, quality requirements, and delivery schedules, are possible using smart contracts [75]. Because of this automation, fewer middlemen are required, which streamlines operations and lowers expenses [76].
3. Supply Chain Visibility: Blockchain technology enables real-time supply chain transparency. There is just one version of the truth since everybody in the network has possession of the same data. This visibility facilitates the detection of inefficiencies, process optimization, and prompt response to supply chain interruptions or modifications [77].
4. Traceability: The The transparency of blockchain allows for the tracing of products across the supply chain. The blockchain tracks every product movement and transaction, making it possible to follow the origin, manufacturing, and distribution history of a given good [78]. This is essential for fulfilling legal requirements and guaranteeing the legitimacy of goods, particularly in sectors like food and medicine where traceability is critical [79].
5. Quality Assurance: With blockchain, the provenance of raw materials and the entire production process can be verified. This is especially crucial in sectors of the economy where quality control is paramount. Producers can guarantee that the raw materials fulfill the required requirements, and customers may trust in the genuineness and excellence of the final product [80].
6. Reduced Fraud and Counterfeiting: The tamper-resistant nature of blockchain helps in reducing fraud and counterfeiting. By creating an unforgeable record of each transaction, blockchain makes it difficult for malicious actors to introduce fake products into the supply chain [81]. This is particularly relevant for industries where counterfeiting is a significant concern [82].
7. Environmental and Social Impact Tracking: Blockchain technology may be used to monitor and validate a product's social and environmental effect. In the context of environmentally friendly supply chain management, this is especially important as businesses want to make sure that their goods are made in a way that is sustainable and ethical. [83]. Blockchain can provide a transparent record of the environmental and social practices at each stage of the supply chain [84].
8. Data Security: Blockchain protects data with state-of-the-art cryptographic techniques. This ensures sensitive data confidentiality and integrity across the supply chain. Participants have control over their own data and can share it selectively with others in the network [85].

Fig. 3 illustrates the links between environmentally conscious supply-chain administration and the use of blockchain technologies. [86].

Implementing blockchain in the context of Industry 4.0 and sustainable supply chain management can lead to more efficient, transparent, and ethical supply chains, contributing to the overall goals of sustainability and responsible business practices [87].

3. Environmental impact monitoring

Blockchain technology allows the environmental impact of an item to be tracked and confirmed along the supply chain. This entails monitoring energy use, carbon emissions, and other sustainability metrics. With the use of this data, supply chains' environmental impact may be decreased, procedures can be optimized, and choices can be made with more knowledge. Blockchain technology may be used to monitor and confirm sustainable supply chain processes [88,89]. Blockchain networks face significant challenges in handling a high volume of transactions due to their consensus mechanisms, which can be time-consuming and resource-intensive. For industrial applications, where transactions occur frequently and need to be processed quickly, the latency and throughput limitations of current blockchain technologies pose a serious bottleneck. It is notoriously energy-intensive which contradicts the principles of sustainability. This is a critical issue when considering blockchain for sustainable supply chain management. This high energy consumption is counterproductive to sustainability goals and poses a significant environmental impact. This is especially significant for sectors of the economy where upholding environmental regulations is essential to sustainable and ethical corporate operations [90]. This feature aids in keeping an unchangeable record of environmental impact data in the context of sustainable supply chain management [91]. Blockchain is notoriously energy-intensive which contradicts the

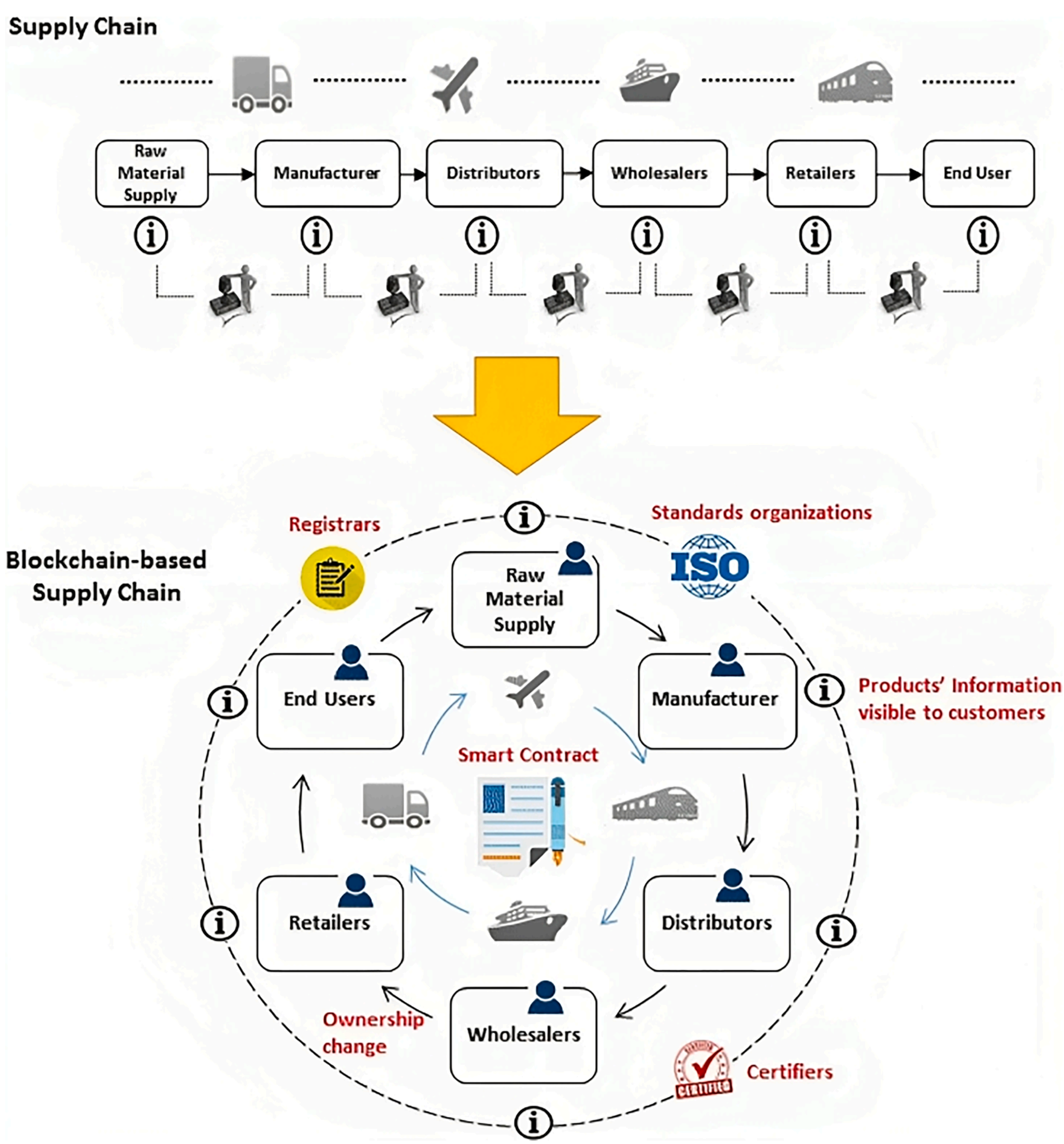

Fig. 3. The links between environmentally conscious supply-chain administration and the use of blockchain technologies [86].

principles of sustainability. This is a critical issue when considering blockchain for sustainable supply chain management. This high energy consumption is counterproductive to sustainability goals and poses a significant environmental impact. Since every member of the network can see any modifications made to the data, accountability and trust are guaranteed.

1. Traceability and Accountability: End-to-end product traceability across the supply chain is made possible by blockchain. The blockchain allows for the recording of every event or transaction pertaining to the manufacture, delivery, and distribution of commodities [92]. This traceability helps in identifying the sources of environmental impact, making it easier to hold responsible parties accountable for their contributions to sustainability issues [93].
2. Smart Contracts for Automated Compliance: Smart contracts, self-executing code on the blockchain, can be employed to automate compliance with sustainability standards and regulations [94]. For instance, predefined rules regarding emissions, waste disposal, or energy consumption can be encoded into smart contracts. When these conditions are met or violated, the smart contract can automatically execute predefined actions, such as triggering alerts or imposing penalties [95].
3. Data Security and Privacy: Blockchain employs cryptographic techniques to secure data, ensuring that information related to environmental impact monitoring is protected from unauthorized access [96]. This is especially crucial when handling sensitive information on environmental rules compliance and sustainability initiatives. [97].
4. Efficient Data Aggregation: IIoT devices generate vast amounts of data. Blockchain facilitates the efficient aggregation and sharing of this data across the supply chain network. This can lead to more accurate and comprehensive environmental impact assessments, enabling companies to make informed decisions to improve their sustainability practices [98].
5. Decentralized Autonomous Organizations (DAOs): Decentralized autonomous organizations that can support group decision-making inside the supply chain network can be established [99]. Stakeholders can participate in the governance of sustainability initiatives, promoting a collaborative and transparent approach to environmental impact management [100].
6. Tokenization for Incentives: Tokenization, creating digital tokens on the blockchain, can be used to incentivize sustainable practices [101]. For instance, companies adhering to eco-friendly processes may receive tokens that can be traded or redeemed for various

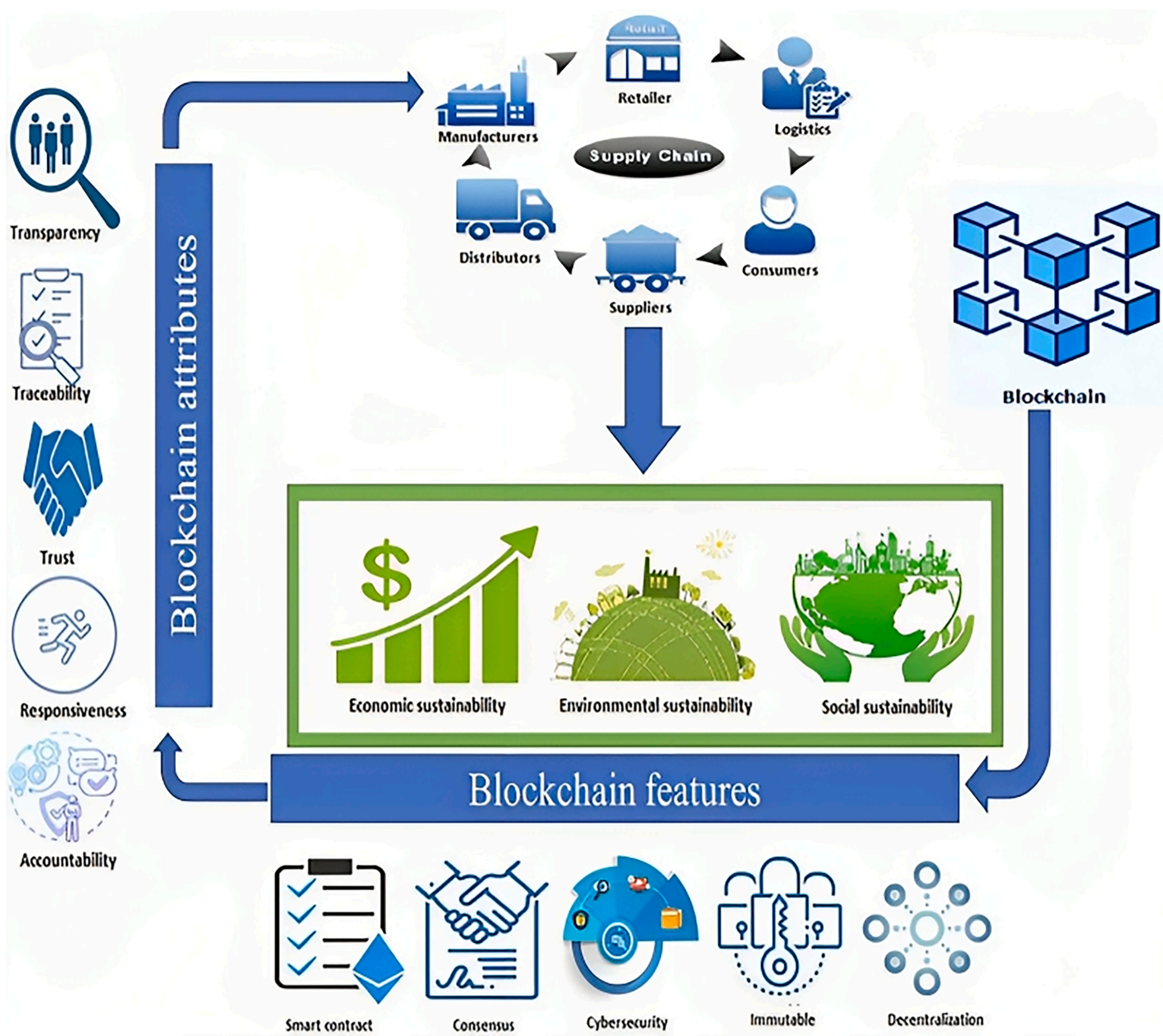

Fig. 4. The application of blockchain to sustainable supply chain management [105].

benefits. This provides a tangible incentive for businesses to adopt and maintain environmentally friendly practices [102].
7. Interoperability and Standardization: Blockchain can contribute to the standardization of data formats and communication protocols within the supply chain. This interoperability ensures seamless integration of various IIoT devices and systems, enabling a more holistic approach to environmental impact monitoring [103,104].

Fig. 4 illustrates how blockchain technology is being applied to environmentally friendly supply chain administration.[105].

Blockchain can track and document the carbon emissions associated with each stage of the supply chain, from raw material extraction to production, transportation, and distribution. By having a tamper-proof record of carbon footprint data, stakeholders can ensure transparency and verify compliance with environmental standards. The technology can also monitor water consumption throughout the supply chain, ensuring that usage is recorded accurately and is in line with sustainability goals. This includes tracking water usage in manufacturing processes, as well as the environmental impact of wastewater discharge. By tracking waste generation, including hazardous and non-hazardous waste, blockchain can provide a transparent record of waste management practices. This helps in ensuring that waste is handled responsibly and recycled or disposed of according to regulations.

In the context of environmental impact monitoring, transparency is crucial for stakeholders to verify that the processes adhere to environmental regulations and sustainability goals. Blockchain technology offers transparency through immutable and verifiable records of transactions and processes. Data privacy, on the other hand, is essential to protect sensitive information that could be misused if publicly accessible. For example, proprietary business processes, competitive strategies, or personal data of employees involved in the IoT systems must remain confidential. Cryptographic techniques employed by blockchain ensure that while the data remains secure and private, the pertinent environmental data can still be made transparent in a controlled manner. Advanced cryptographic techniques like zero-knowledge proofs can be used. These techniques allow auditors to verify the environmental compliance without accessing the underlying sensitive data, thus maintaining privacy.

By combining blockchain technology with IIoT in the context of sustainable supply chain management, Industry 4.0 can achieve more accurate, transparent, and accountable environmental impact monitoring, contributing to the overall goal of building a more sustainable and responsible industrial ecosystem [106].

4. Smart contracts for automation

When certain criteria are satisfied, smart contracts—programmable code on the blockchain—can automate and carry out a number of supply chain operations. This can minimize delays and cut down on the need for middlemen by streamlining and automating some supply chain processes [107]. By eliminating the need for middlemen and automating payments when specific criteria are satisfied, smart contracts can simplify and expedite the payment process [108]. Additionally, smart contracts have the ability to automate a number of procedures, including payment upon successful delivery of products, quality control, and order fulfillment. When specific requirements are satisfied (e.g., arrival of goods at a specific location), smart contracts can automatically trigger the next set of actions. IIoT sensors can trigger smart contracts based on predefined criteria, streamlining operations [109,110]. Here are several key aspects to consider:

Transparency and Traceability: Blockchain provides a distributed, verifiable ledger that records each transaction done across a network. In the context of supply chain management, this ensures material accountability and traceability from the point of origin to the end user [111]. The blockchain allows for the immutable and auditable recording of every event or transaction in the supply chain [112].

1. Smart Contracts for Automation: Smart contracts, which are self-executing arrangements with the terms of the agreement expressly encoded into the code, can automate a number of supply chain processes. For instance, the smart contract can automatically start the next stage of the business, like payment or the start of the next manufacturing phase, when specific conditions are satisfied (such delivery confirmation or quality inspection) [113,114].
2. Enhanced Security: The encrypted and decentralized features of blockchain improve data and transaction security. This is especially important in Industry 4.0 since there are a lot of internet-connected equipment and sensors [115]. Blockchain ensures that data integrity is maintained, and unauthorized access or tampering is minimized [84].
3. Efficient Data Management: IIoT generates a vast amount of data from sensors and devices. Blockchain can be used to manage and store this data efficiently [116]. By distributing the data across the network, it reduces the reliance on a central authority and minimizes the risk of a single point of failure [117].
4. Supply Chain Optimization: Utilizing blockchain and IIoT allows for real-time monitoring of the supply chain. This real-time visibility enables quick responses to disruptions, improves overall efficiency, and helps in optimizing the supply chain processes [114,118].
5. Decentralization and Peer-to-Peer Transactions: Blockchain eliminates the need for intermediaries in transactions. In a supply chain, this means that parties can engage in peer-to-peer transactions with trust, reducing delays and costs associated with intermediaries.
6. Sustainability and Compliance: Blockchain technology may be used to monitor and confirm a product's sustainability credentials [119]. In the current corporate context, when customers are becoming more concerned about the environmental and social effect of the items they buy, this is especially crucial. Throughout the supply chain, smart contracts may be used to enforce adherence to sustainability norms [110,120].
7. Interoperability: Blockchain can facilitate interoperability between different systems within Industry 4.0. This is crucial for ensuring that data from various sources can be seamlessly integrated and utilized for better decision-making [121].

The applications of blockchain to smart contracts and supply chain management is shown in the Fig. 5 [122].

In summary, the combination of blockchain and IIoT, along with the use of smart contracts, can revolutionize supply chain management in Industry 4.0. It brings about transparency, efficiency, security, and sustainability, contributing to the overall advancement of smart and sustainable manufacturing practices [123].

5. Efficient data management

Blockchain offers an effective and safe method of managing the massive amounts of data produced by IoT devices in Industry 4.0 [124]. It helps in streamlining data sharing across the supply chain while maintaining data integrity [125]. Here's an overview of how blockchains can contribute to this aspect:

1. Decentralized and Distributed Ledger: Blockchain technology uses data integrity to create a distributed, decentralized ledger where data is held across a network of nodes. By doing this, a single point of failure is avoided and data integrity is ensured. Because all supply chain participants have access to the same, unchangeable records, there is less chance of fraud or data tampering [126]. Lastly, information put to the blockchain cannot be removed or changed. A reliable and impenetrable record of the events and transactions in the supply chain is ensured by the immutability [127,128].
2. Smart Contracts: Supply chain operations may be automated through the use of smart contracts, which are self-executing agreements with the conditions of the agreement encoded directly into the code

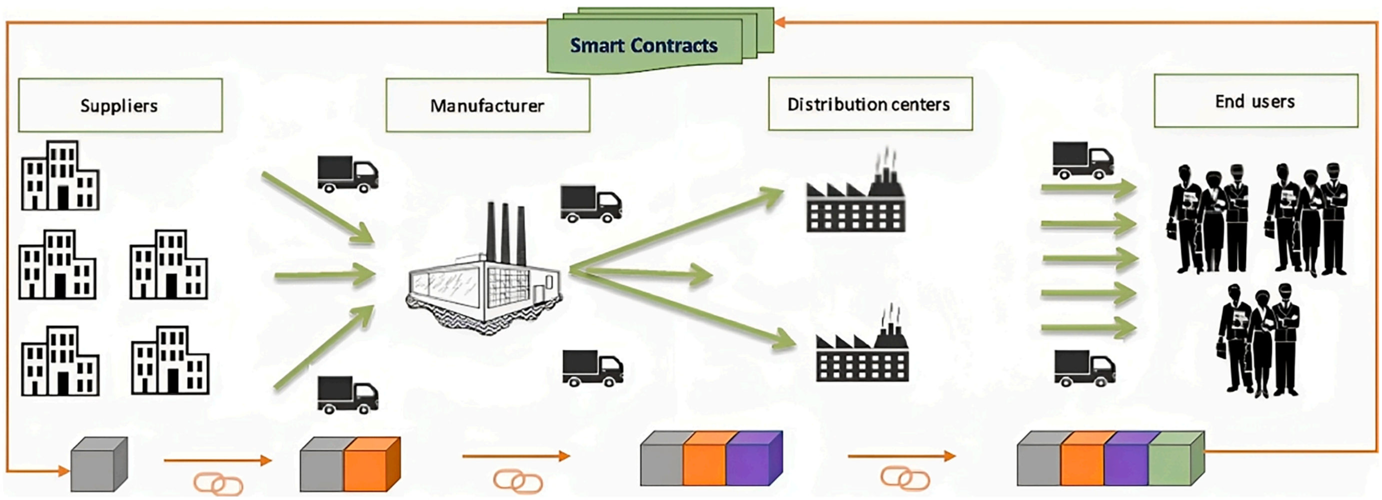

Fig. 5. The applications of blockchain to smart contracts and supply chain management [122].

[129]. This involves setting off events like as payments, order fulfillment, or quality control in response to certain thresholds being reached. This automation simplifies processes and lessens the need for middlemen [130].

3. Supply Chain Traceability: Supply chain traceability and end-to-end visibility are made possible by blockchain. Because every transaction is documented on the blockchain, all parties involved can follow a product's path from point of origin to final customer [131]. For sustainable and ethical behaviors to be real, there must be transparency [132].
4. Data Security and privacy using encryption and consensus mechanisms: Blockchains use advanced encryption techniques to secure data. Moreover, consensus techniques ensure that all network participants agreed on the validity of transactions [109]. This enhances data security and privacy, crucial aspects in the context of sensitive industrial and supply chain data [133].
5. Efficient Collaboration: Interoperability: Blockchain technology can facilitate interoperability among different systems and stakeholders in the supply chain [130]. This ensures seamless communication and collaboration between various entities, promoting a more efficient and integrated supply chain ecosystem [134].
6. Real-time Monitoring: Timely and Accurate Data: The decentralized nature of blockchains allows for real-time updates and monitoring of events in the supply chain. This is particularly beneficial for Industry 4.0, where the ability to react quickly to changes in demand, logistics, or production is essential for efficiency [135].
7. Reduced Costs: Elimination of Intermediaries: By automating processes through smart contracts and providing a trustful environment, blockchains can reduce the need for intermediaries, resulting in cost savings for supply chain participants [136].

An industrial blockchain-based system and internet of things for evaluating green supply chains and circular economies is shown in the Fig. 6 [137].

In summary, integrating blockchains into the Industrial Internet of Things for sustainable supply chain management in Industry 4.0 enhances data management efficiency by ensuring data integrity, automating processes, enabling traceability, enhancing security, promoting collaboration, and reducing costs. This integration holds great potential for creating more resilient, transparent, and sustainable supply chains.

6. Data security and integrity

Blockchain shares data among a network of nodes as an alternative to depending on a database or a central authority. Decentralized blockchain systems eliminate the need for an executive branch by spreading data across their nodes. This reduces the chance of a single point of failure and increases the system's resilience. An ecosystem of the supply chain that is more democratic and cooperative can also benefit from decentralization [138,139]. While blockchain provides enhanced security features such as immutability and decentralized control, IIoT networks themselves pose unique security challenges. IIoT devices can be

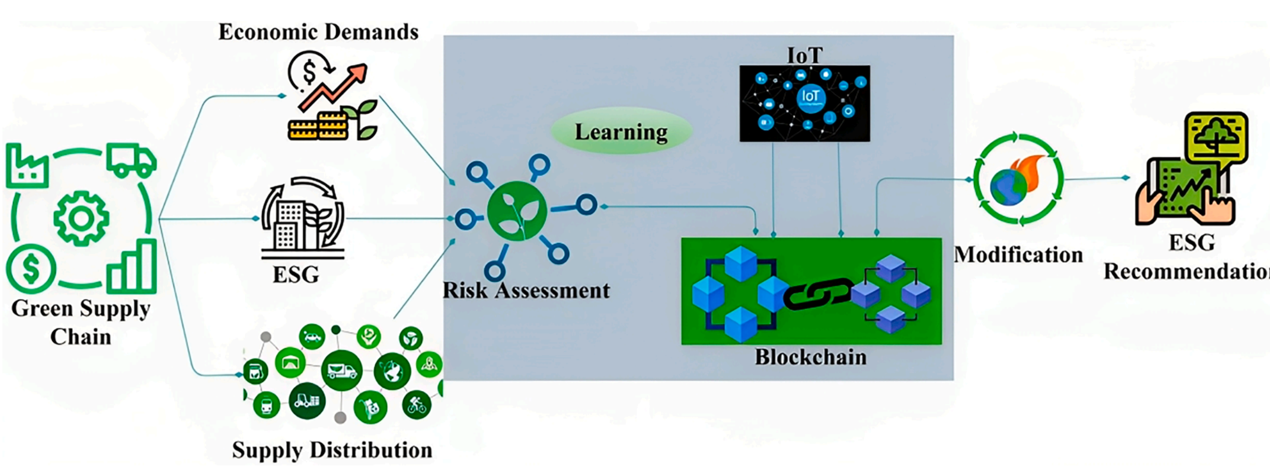

Fig. 6. An industrial blockchain-based system and internet of things for evaluating green supply chains and circular economies [137].

vulnerable to attacks due to their often limited computational capabilities and varying security standards. Issues such as firmware tampering, unauthorized access, and data breaches are concerns that need to be addressed. By lowering the possibility of data tampering or a single point of failure, this decentralized method improves security. Cryptographic methods are used to safeguard blockchain transactions, guaranteeing the data's integrity and secrecy. This is especially important for businesses where tampering with data might have serious repercussions [140]. IIoT devices that are blockchain-connected may send data with assurance that it is real [141]. Here's an overview of how blockchain contributes to data security and integrity in the sustainable supply chain management of Industry 4.0:

1. Immutable Ledger by Data Integrity: Blockchain uses a distributed, decentralized ledger to guarantee data integrity. After information is entered into a block, it is connected to the preceding block in a way that makes manipulation exceedingly challenging. Because of its immutability, the data is safe and unchangeable, making it a trustworthy source of truth across the supply chain [142].
2. Decentralization: Traditional centralized databases are susceptible to single points of failure and security breaches. Blockchain's decentralized nature eliminates the vulnerability associated with centralized systems. Even if one node is compromised, the majority of the network remains secure, ensuring continuous data availability [143].
3. Smart Contracts by Automated Trust: Business rules can be automated and enforced by smart contracts. These are self-executing agreements with particular terms embedded into the source code [144]. Smart contracts can help with automated payments, transactions, and even the enforcement of sustainability criteria in supply chain management. As a result, there is less need for middlemen and less chance of fraud [145].
4. Transparency: Supply chain traceability and end-to-end visibility are made possible by blockchain. Any member of the network may access an unchangeable, transparent record of each transaction, from the procurement of the initial supplies to the delivery of the finished product. This transparency reduces waste, ensures compliance with environmental regulations, and aids in identifying inefficiencies [146].
5. Security against Cyber Threats by Encryption and Consensus: Blockchain secures data by using cryptographic techniques to prevent unwanted access. Consensus techniques guard against malicious actors changing data by ensuring that all participants concur on the legitimacy of transactions. This improves the supply chain's overall cybersecurity [147,148].
6. Tokenization of Assets: Blockchain makes it easier to tokenize both physical as well as digital assets, giving every item in the supply chain an electronic representation. This not only helps in tracking the origin and movement of assets but also ensures that only authorized entities can access and modify the corresponding digital records [135,149].
7. Efficient Auditing by Real-time Audits: Traditional audits in supply chain management can be time-consuming and resource-intensive. With blockchain, auditing becomes more efficient as all relevant information is readily available on the distributed ledger. This not only reduces the risk of errors but also allows for real-time auditing [150].
8. Cross-Organizational Collaboration: Blockchain makes it easier for many supply chain participants, including manufacturers, suppliers, shipping companies, and regulators, to work together seamlessly. This interoperability streamlines data sharing, leading to improved efficiency and sustainability practices.

Blockchain, Internet of Things, and edge computing technologies in supply chain management is shown in the Fig. 7 [151].

In the context of Industry 4.0, blockchain technology improves the security, transparency, and effectiveness of data management by tackling these factors, which helps to create environmentally friendly supply chains.

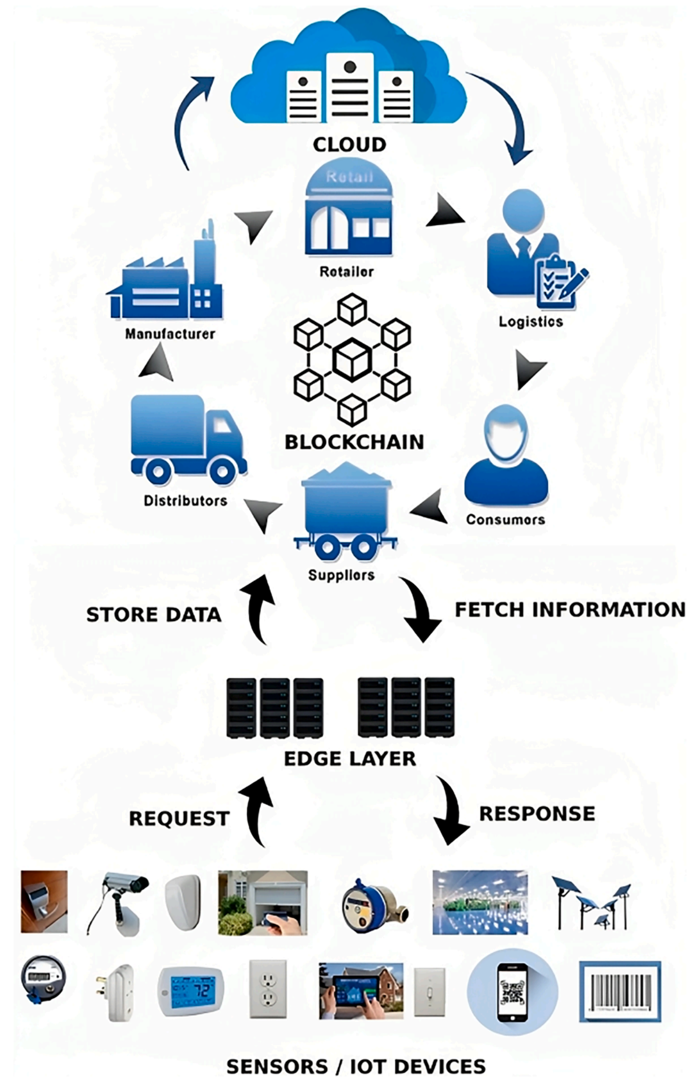

Fig. 7. Blockchain, Internet of Things, and edge computing technologies in supply chain management [151].

7. Efficient and real-time monitoring systems

The integration of blockchain technology with Internet of Things (IoT) devices, like as sensors and RFID tags, can facilitate the real-time monitoring of environmental and asset status across the supply chain. Large volumes of real-time data are produced by IIoT devices. Throughout the supply chain, assets and operations may be securely and instantly monitored with the integration of blockchain [152]. Quick reactions to problems are made possible by this real-time visibility, which lowers the possibility of disruptions and increases overall efficiency. Because blockchain is decentralized, there are fewer inconsistencies and mistakes because everyone has access to the most recent, consistent version of the data [5,79]. Here are some ways in which blockchain can contribute to efficient and real-time monitoring in this domain:

1. Transparency and Traceability: A transparent and immutable ledger that can be employed to track and record every event or transaction that takes place across the supply chain is provided by

the technology of blockchain [153]. This guarantees traceability and transparency and gives stakeholders access to a product's whole history, from its place of origin to its present position [154].
2. Smart Contracts: Smart agreements, which are self-executing, have clear contract requirements embedded into their code. Smart contracts automatically verify the authenticity and accuracy of this data by cross-referencing it with predefined standards or historical data stored on the blockchain. In the IIoT ecosystem, smart contracts can streamline and automate various supply chain processes, ensuring timely and precise execution of tasks. By enabling efficient and real-time monitoring systems, smart contracts not only enhance operational efficiency and transparency but also support sustainability initiatives [155].
3. Real-time Monitoring: IIoT devices, such as sensors and RFID tags, generate vast amounts of data. Blockchain can be integrated with these devices to create a secure and decentralized system for real-time monitoring [127]. This can support the monitoring of environmental conditions, the tracking of the movement of commodities, and the assurance of regulatory compliance [156].
4. Data Integrity: Data integrity is guaranteed by the decentralized and impenetrable nature of blockchain technology. Blockchain can prohibit unauthorized changes to information, lowering the risk of fraud and errors in a supply chain where data accuracy is crucial [157].
5. Decentralization: Because blockchain technology is decentralized, there is no longer a need for a central authority, which lowers the possibility of a single point of failure. This can enhance the supply chain system's overall robustness and dependability [158].
6. Supply Chain Visibility: Real-time visibility across the supply chain is made possible by blockchain. This insight may assist in finding inefficiencies, cutting down on delays, and streamlining the supply chain procedure as a whole.
7. Provenance Tracking: Provenance tracking is crucial in industries where the origin and authenticity of products are significant, such as in the food and pharmaceutical industries. Blockchain can provide an immutable record of the origin, manufacturing, and distribution of products [91].
8. Environmental Impact Tracking: With an increased focus on sustainability, blockchain can be used to track and verify the environmental impact of products. This includes monitoring carbon footprints, adherence to sustainability standards, and the use of eco-friendly materials [81,159].
9. Collaboration and Trust: Blockchain fosters trust among participants in the supply chain by providing a shared, transparent, and tamper-proof ledger. This encourages collaboration among stakeholders who may not fully trust each other in a traditional supply chain setup.
10. Efficient Auditing: Auditing and compliance processes can be streamlined through blockchain. Because the technology is transparent and decentralized, audits may be conducted more effectively and reliably, saving money and time on compliance checks.

System architecture for container operations at a port enabled by IoT is shown in Fig. 8 [160].

Implementing blockchain in the using of industrial internet of things for managing supply chains requires collaboration among industry players, standards development, and overcoming technical challenges. However, the potential benefits in terms of efficiency, transparency, and sustainability make it an area of considerable interest and ongoing research within Industry 4.0 [131].

8. Supply chain optimization

Analyzing the data saved on the blockchain allows for the identification of supply chain patterns, inefficiencies, and opportunities for improvement. By streamlining procedures and cutting waste, this data can help achieve sustainability objectives. Supply chain operations may be made more efficient by applying machine learning algorithms to the data kept on the blockchain [71,161]. This results in resource efficiency and waste reduction and comprises demand forecasting, inventory management, and transportation logistics [73]. Here's an overview of how blockchain can be leveraged in the sustainable supply chain management of Industry 4.0:

1. Transparency and Traceability: All supply chain actors can see the same, unchangeable record of transactions and product movements thanks to blockchain's transparent and unchangeable ledger. Because of its increased openness, items can now be tracked in real time from their point of origin to every point in the supply chain. Adherence to sustainability norms and laws is crucial [162].
2. Smart Contracts: Smart agreements, which are self-executing agreements containing the terms of the agreement expressly

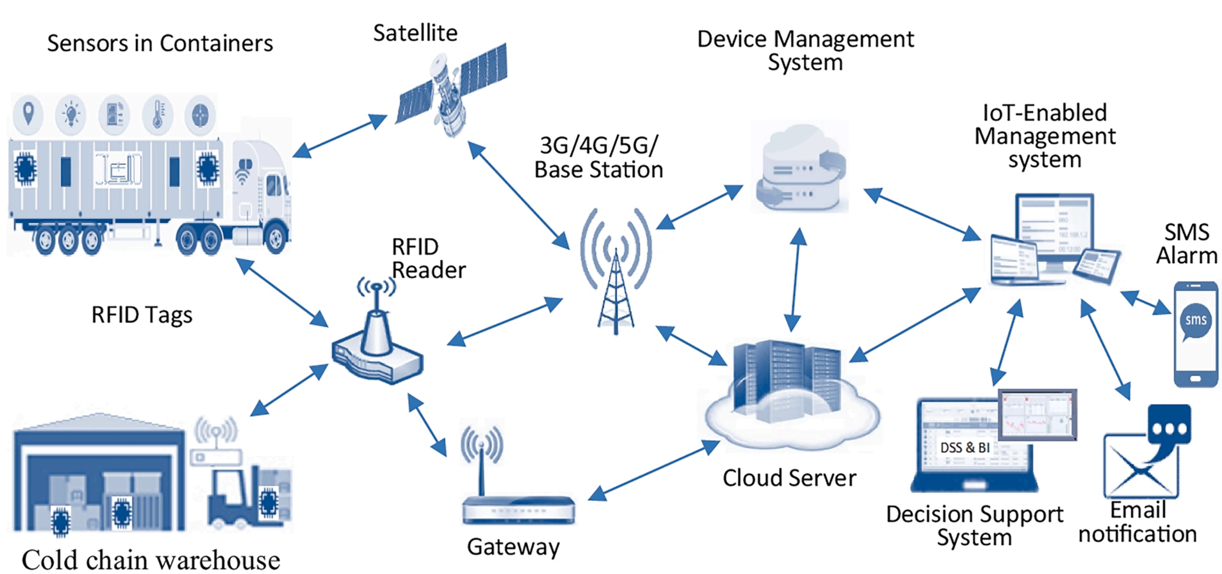

Fig. 8. System architecture for container operations at a port enabled by IoT [160].

encoded into the code, can automate a number of operations in the supply chain. Transactions are sped up, mistakes are reduced, and middlemen are less necessary because to this automation [163]. Smart contracts may be designed to enforce and track compliance with environmentally friendly norms and practices at every point in the supply chain when it comes to sustainability [164].
3. Data Security and Privacy: Data security and integrity are guaranteed by the distributed and encrypted nature of blockchain. This is especially important in Industry 4.0, where large volumes of sensitive data are generated by IoT devices. Protecting sensitive sustainability-related data is essential, and blockchain's secure and tamper-resistant structure contributes to maintaining the confidentiality and privacy of such information [123,165].
4. Supply Chain Optimization: Blockchain facilitates real-time information sharing across the supply chain, reducing delays and inefficiencies. This is particularly beneficial for optimizing logistics, inventory management, and production processes. Improved visibility into the supply chain helps identify areas for optimization, leading to reduced waste, energy consumption, and overall resource utilization.
5. Quality Assurance and Certification: Blockchain can be used to store and verify certifications and compliance documents related to sustainable practices. This ensures that products meet specific environmental and ethical standards [166]. Consumers, regulators, and stakeholders can easily access this information, fostering trust in the supply chain and encouraging companies to adopt more sustainable practices.
6. Decentralized Energy Management: In Industry 4.0, many devices are interconnected and require energy. Blockchain can enable decentralized energy management, optimizing energy usage and distribution across the supply chain [167]. This contributes to sustainability goals by promoting energy efficiency and reducing the carbon footprint associated with energy consumption [168].
7. Carbon Footprint Tracking: Blockchain can be used to track and record the carbon footprint of products throughout the supply chain [169]. This information can be valuable for companies aiming to reduce their environmental impact and for consumers who prioritize eco-friendly products.

Blockchain in the logistics and supply chain sector is shown in the Fig. 9 [3].

In summary, the combination of blockchain and IIoT in the context of Industry 4.0 offers a robust framework for creating more sustainable and optimized supply chains. It enhances transparency, automates processes, ensures data security, and supports the tracking of sustainability metrics throughout the entire supply chain [170].

9. Compliance and certification

Integrating socially and ecologically conscious methods into supply chain operations is known as sustainable supply chain management. The use of Industry 4.0 concepts, such as automation and digital technology adoption, augments the supply chain's capabilities. It is possible to construct smart contracts to make sure that supply chain actors follow sustainability and legal requirements. This can lower the risk of non-compliance and streamline compliance management [162]. It could entail utilizing blockchain technology to provide an open, safe system for monitoring and documenting supply chain transactions. This can guarantee data integrity, improve product traceability, and make it easier to comply with laws and industry norms [171]. Additionally, the use of blockchain in combination with IIoT devices can contribute to more sustainable practices in the supply chain, aligning with the principles of Industry 4.0 [96,172]. Moreover, compliance with relevant laws and standards is essential in modern industrial practices. Blockchain's transparent and immutable nature aids in ensuring compliance by providing a traceable and auditable record of transactions. Certification processes are streamlined and made more reliable through blockchain, offering a secure way to verify that products, processes, or systems meet required standards [173]. Finally, obtaining certifications can provide official recognition of the compliance and sustainability efforts undertaken in the supply chain management process [174]. In summary, Industry 4.0 concepts are aligned with blockchain integration in IIoT for Sustainable Supply Chain Management, improving compliance, efficiency, and transparency in the industrial ecosystem [175].

10. Current real-world IoT-blockchain implementation issues

One of the major hurdles in implementing blockchain in IIoT systems is the choice of consensus mechanism. Proof of Work (PoW), used by Bitcoin and other cryptocurrencies, is computationally intensive and energy-consuming, making it impractical for IIoT environments characterized by resource-constrained devices. On the other hand, Proof of

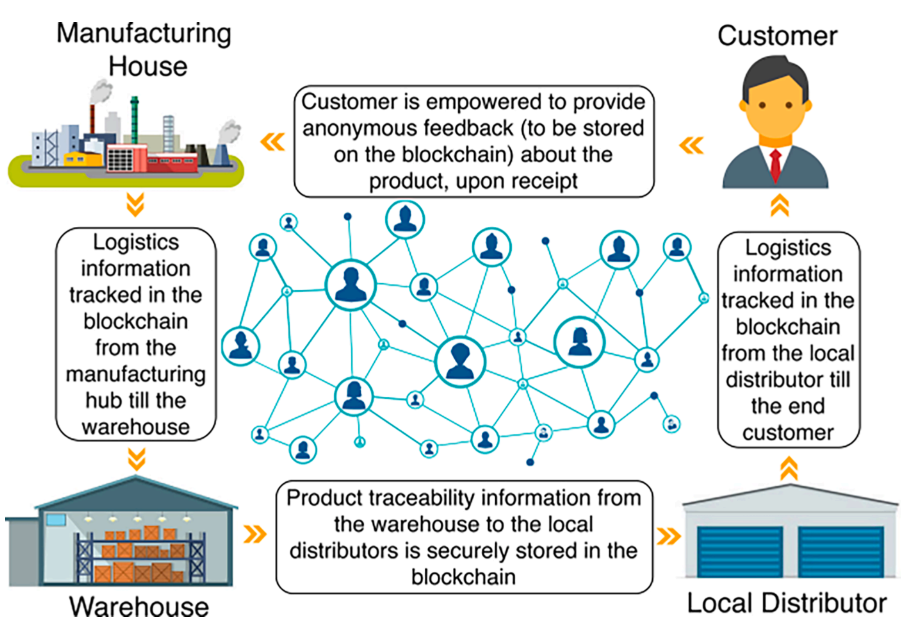

Fig. 9. Blockchain in the logistics and supply chain sector [3].

Stake (PoS), which selects validators based on their stake in the network, offers a more energy-efficient alternative but may introduce concerns regarding centralization and security. Understanding the trade-offs between these mechanisms is crucial for optimizing blockchain integration in IIoT applications. Blockchain can facilitate secure and decentralized device-to-device authentication, reducing the reliance on centralized data pools. This approach not only enhances security by eliminating single points of failure but also speeds up transactions as devices can authenticate and communicate directly. Implementing robust blockchain-based authentication protocols is essential for maintaining data integrity and operational efficiency in IIoT networks. Scalability remains a significant challenge for both IoT and blockchain systems. The proliferation of IIoT devices leads to an exponential increase in data generation, which blockchain networks must efficiently handle. Traditional blockchain networks struggle with limited throughput and high latency, which can hinder real-time IIoT applications. To address these scalability issues, several approaches are being explored:

1. Sharding: This technique involves splitting the blockchain into smaller, manageable segments (shards) that can process transactions in parallel, thereby increasing throughput.
2. Off-Chain Solutions: These include the use of sidechains or state channels that handle transactions off the main blockchain, reducing congestion and improving speed.
3. Advanced Consensus Algorithms: Emerging consensus mechanisms, such as Delegated Proof of Stake (DPoS) and Byzantine Fault Tolerance (BFT), offer improved scalability and performance suitable for IIoT applications.

11. Tokenization for incentives

Blockchain allows for the creation of token-based systems that can be used to incentivize sustainable practices within the supply chain. Participants can be rewarded with tokens for environmentally friendly actions, creating a system that encourages sustainability. Tokenization is introduced to create digital tokens that represent various assets or aspects within the supply chain [176]. These tokens can be used to incentivize and reward participants for sustainable practices. For example, manufacturers, suppliers, or logistics partners might receive tokens for using eco-friendly practices or meeting certain sustainability criteria. The integration of tokenization for incentives aligns with the principles of Industry 4.0, promoting a more sustainable and efficient supply chain [177]. Participants in the supply chain are motivated to adopt environmentally friendly practices, ultimately contributing to a more sustainable and responsible industrial ecosystem [178]. Tokenization can play a crucial role in providing incentives and optimizing processes within this framework.

1. Blockchain in IIoT for SSCM: Through the application of transparency and traceability, the use of blockchain technology makes it possible to create an immutable, decentralized ledger that guarantees the safety and transparency of commodities along the supply chain. This is particularly important in SSCM for tracking production processes, determining the origin of raw materials, and verifying the authenticity of items [179]. Additionally, a number of SSCM operations may be automated via smart contracts, which are self-executing agreements with the conditions of the agreement explicitly put into code. To ensure confidence and lessen the need for middlemen, they might, for example, enable automated payments following the fulfillment of predetermined conditions. Furthermore, a great deal of data is generated by IIoT devices, and it is crucial to guarantee the security and integrity of this data. Blockchain's decentralized structure and cryptographic capabilities improve data security by lowering the possibility of manipulation and unwanted access [180]. Furthermore, the absence of a single point of failure in the system is guaranteed by the decentralized nature of blockchain. This might be especially crucial for preserving the uninterrupted functioning of IIoT equipment and averting supply chain interruptions [114,181].
2. Tokenization for Incentives: Tokenization can facilitate supply chain financing by representing assets or invoices as tokens on the blockchain. This allows for more efficient and transparent financing options, where stakeholders can tokenize their assets and access funding based on the value represented by these tokens. Tokens can be also used to incentivize sustainable practices within the supply chain. For example, participants who adopt eco-friendly manufacturing processes or use sustainable materials can be rewarded with tokens [182]. This encourages environmentally responsible behavior and contributes to the overall sustainability goals of the supply chain. Moreover, Tokens can be employed to reward efficiency improvements in the supply chain. Smart contracts can be designed to automatically distribute tokens to participants who streamline their processes, reduce waste, or enhance overall efficiency, thus promoting continuous improvement [183]. Tokens can also be issued to stakeholders such as suppliers, manufacturers, and distributors, creating a shared incentive system. This can enhance collaboration, trust, and communication among different parties in the supply chain, fostering a more interconnected and efficient ecosystem [175].

In summary, by incorporating tokenization, IIoT, and blockchain technology into SSCM for Industry 4.0, supply chain processes might be substantially changed. This would improve the efficacy, sustainability, and transparency of supply chain procedures. This convergence is consistent with the overall goals of Industry 4.0, which seeks to benefit several industries and the public at large by utilizing cutting-edge technology [184].

12. Decentralized Autonomous Organizations (DAOs)

Blockchain can facilitate the creation of DAOs, where stakeholders collectively make decisions about supply chain operations. This decentralized approach promotes collaboration and can lead to more sustainable and consensus-driven practices [152]. Additionally, the concept of Decentralized Autonomous Organizations (DAOs) further enhances the decentralization aspect, providing new possibilities for governance and decision-making. Let's explore each of these components:

1. Blockchain for IIoT in Sustainable Supply Chain Management: Data cannot be changed once it is recorded because to blockchain's decentralised and unchangeable nature. For supply chains to be traceable and transparent, this characteristic is essential [185]. Each participant in the supply chain, including manufacturers, suppliers, logistics providers, and customers, can access a shared ledger that provides real-time information about the flow of goods [79]. Additionally, a number of supply chain procedures can be automated by using smart contracts, which are self-executing agreements with the terms of the agreement explicitly encoded into the code. For instance, they have the ability to initiate payments automatically upon the fulfillment of specific requirements, such a successful delivery or quality assurance [186]. The decentralized architecture of blockchain enhances data security. Each participant has control over their data, and cryptographic techniques ensure the integrity and confidentiality of information. Moreover, Blockchain can reduce delays and errors in the supply chain by providing a single, shared source of truth. This reduces the need for reconciliation among multiple parties and streamlines processes [187]. The transparency and traceability enabled by blockchain can also help identify inefficiencies and areas for improvement in the supply chain, leading to more sustainable practices. This is especially crucial in light of

Industry 4.0, which places an increasing focus on social and environmental responsibilities.

2. Decentralized Autonomous Organizations (DAOs): Decentralized autonomous groups (DAOs) are open, member-controlled, and run by computer programs that include rules rather than having centralized authorities. DAOs can support decentralised decision-making processes inside Industry 4.0. Voting on supply chain plans, resource distribution, and sustainability projects are a few examples of this. Additionally, the majority of DAOs run on a consensus method in which participants can cast votes according to the quantity of tokens they own. This establishes an open and democratic system of government. Voting is available for suggestions pertaining to organizational norms, sustainability projects, and supply chain enhancements [177]. DAOs often use tokens for voting and governance. These tokens can also represent ownership stakes or voting power within the organization. Tokenization can provide economic incentives for participants to contribute positively to the supply chain and sustainability efforts. Moreover, the DAOs enable trustless collaboration, meaning that participants can engage in transactions and decision-making without needing to trust a central authority. This aligns with the decentralized and trustless principles of blockchain technology [178,188].

In summary, combining blockchain, IIoT, and DAOs in the context of Industry 4.0 can lead to a more transparent, efficient, and sustainable supply chain. This integration has the potential to reshape traditional business models and foster a new era of decentralized and collaborative industrial ecosystems.

13. Real-time data sharing

Large volumes of real-time data are produced by IIoT devices. Blockchain makes it possible for pertinent supply chain parties to share this data securely and instantly. IIoT makes it possible to manage and monitor different components in real-time within the context of supply chain management. This enhances collaboration and decision-making capabilities [132,139]. In the context of supply chain management, real-time data sharing involves the instantaneous exchange of information among various stakeholders in the supply chain [189]. This makes decision-making easier, cuts down on delays, and boosts productivity all around. Its objectives are to protect the environment, make the best use of available resources, and guarantee moral behavior [190]. The integration of blockchain in IIoT for supply chain management in Industry 4.0 brings several benefits, such as:

- Security: Data security is enhanced by blockchain's cryptographic features.
- Transparency: Transparency is encouraged since all parties are in possession of the same information.
- Traceability: Every transaction or data point is traceable, helping to identify the source of any issues.
- Efficiency: Real-time data sharing facilitates quicker responses to changes or disruptions in the supply chain [191].

An end-to-end blockchain-based food logistics approach is shown in the Fig. 10 [192].

While the combination of blockchain and IIoT offers numerous advantages, challenges include scalability, interoperability, and the need for industry-wide standards. In summary, leveraging blockchains in IIoT for sustainable supply chain management in the Industry 4.0 context enables secure and transparent real-time data sharing, contributing to more efficient, sustainable, and resilient industrial processes [115,193].

14. Challenges and limitations

There are several challenges for the blockchains for industrial internet of things in sustainable supply chain management of industry 4.0 which can be presented as,

1. Scalability: One of the primary challenges facing blockchain technology is scalability. As the volume of transactions increases within a

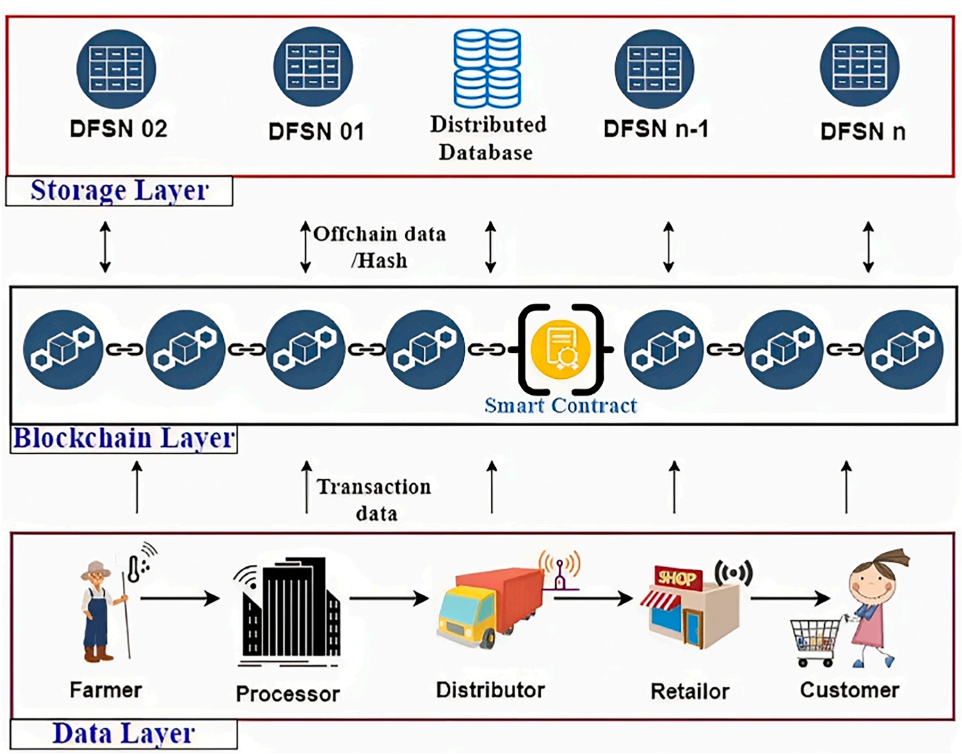

Fig. 10. An end-to-end blockchain-based food logistics approach [192].

supply chain network, the blockchain network may struggle to process and validate transactions efficiently.
2. Interoperability: Achieving seamless interoperability between different blockchain platforms and existing enterprise systems poses a significant challenge. Supply chains typically involve multiple stakeholders using diverse systems and technologies.
3. Data Privacy and Security: While blockchain offers inherent security features such as immutability and cryptographic encryption, ensuring the privacy and security of sensitive supply chain data remains a concern.
4. Costs and Complexity: Implementing blockchain technology in supply chain management involves significant upfront costs and complexity. Organizations need to invest in infrastructure, development, and ongoing maintenance of blockchain networks.
5. Environmental Concerns: The energy consumption associated with blockchain consensus mechanisms, such as proof of work (PoW), has raised concerns about the environmental impact, especially as sustainability becomes a key focus in Industry 4.0 initiatives. Addressing these concerns may require exploring alternative consensus mechanisms or improving the energy efficiency of blockchain networks.
6. Adoption and Governance: Encouraging widespread adoption of blockchain technology across supply chain networks requires overcoming resistance to change and establishing governance structures that promote collaboration and consensus among stakeholders.
7. Technology Maturity and Standards: Blockchain technology is still relatively young, and standards and best practices for its implementation in supply chain management are evolving.

Collaboration between industry stakeholders, academia, and policymakers is essential to drive innovation, establish standards, and realize the full potential of blockchain in sustainable supply chain management within the context of Industry 4.0.

15. Conclusion

The integration of the Industrial Internet of Things (IIoT) in Sustainable Supply Chain Management (SSCM) within the context of Industry 4.0 marks a pivotal step towards achieving heightened efficiency, transparency, and environmental responsibility in modern industrial practices. The symbiotic relationship between IIoT and SSCM empowers industries to transcend traditional supply chain models, fostering a more agile, responsive, and sustainable ecosystem. It can enhance transparency, efficiency, and sustainability in supply chain management. Also, it provides a foundation for creating a more resilient, secure, and environmentally friendly industrial ecosystem. Implementing blockchain in the IIoT for sustainable supply chain management in Industry 4.0 requires collaboration among stakeholders, standardization of protocols, and addressing scalability challenges. As the technology matures and adoption increases, it has the potential to revolutionize how industries manage and optimize their supply chains in a sustainable manner. Blockchain-based systems can include mechanisms for rewarding sustainable practices. For example, suppliers adhering to certain environmental standards could receive tokens or other incentives, fostering a more sustainable supply chain. IIoT devices contribute to the optimization of the supply chain by providing data on equipment health, inventory levels, and production efficiency. This data, when combined with blockchain, enables predictive maintenance and just-in-time inventory management.

The real-time data acquisition, monitoring, and analysis capabilities afforded by IIoT technologies enable unprecedented visibility across the entire supply chain, facilitating informed decision-making and optimizing resource utilization. Through the seamless connectivity of devices, machines, and processes, Industry 4.0 not only streamlines operations but also mitigates risks and enhances overall resilience in the face of unforeseen disruptions.

Furthermore, the amalgamation of IIoT and SSCM aligns with the global imperative for sustainable development. By promoting eco-friendly practices, reducing waste, and minimizing the environmental footprint of supply chain operations, Industry 4.0 contributes significantly to corporate social responsibility and regulatory compliance. This holistic approach not only safeguards the planet but also resonates with consumers and stakeholders increasingly prioritizing ethical and sustainable business practices.

The effective integration of IIoT in SSCM will depend on cooperation between industry participants, legislators, and technology suppliers as we go into the era of Industry 4.0. Getting beyond obstacles with data security, interoperability, and workforce upskilling will be critical to realizing this game-changing synergy's full potential. Nonetheless, firms hoping to prosper in a quickly changing and linked global economy must pursue IIoT-enabled Sustainable Supply Chain Management due to the advantages of increased efficiency, decreased costs, and environmental stewardship. To put it simply, the combination of IIoT and SSCM signals the beginning of a new chapter in industrial sustainability, one in which innovation and accountability come together to create a future that is not just highly technologically sophisticated but also socially and ecologically conscious.

16. Future research work directions

Future research opportunities abound when it comes to the integration of Industrial Internet of Things (IIoT) with Sustainable Supply Chain Management (SSCM) within the framework of Industry 4.0. Here are several potential research directions:

1. Integration of IIoT and Sustainability Metrics:
   - Explore how IIoT technologies can be integrated into existing sustainability metrics and frameworks. This involves developing new indicators that leverage real-time data from the IIoT to measure and monitor environmental, social, and economic impacts.
2. Energy Efficiency and Resource Optimization:
   - Investigate how IIoT devices can be utilized to optimize energy consumption and resource utilization in supply chain operations. This includes the development of smart algorithms and systems for predictive maintenance, energy-efficient routing, and demand-driven production.
3. Blockchain for Transparent and Traceable Supply Chains:
   - Examine the potential of combining IIoT and blockchain technologies to create transparent and traceable supply chains. This could enhance trust among stakeholders by providing an immutable and secure ledger of transactions, ensuring the authenticity of sustainable practices.
4. Circular Economy Implementation:
   - Explore how IIoT can facilitate the transition to a circular economy by enabling better tracking, recycling, and reuse of materials throughout the supply chain. Investigate the implementation of smart contracts and sensors to support reverse logistics and closed-loop supply chain models.
5. Risk Management and Resilience:
   - Assess how IIoT technologies can contribute to risk management and enhance the resilience of supply chains in the face of disruptions, whether they be environmental, geopolitical, or related to pandemics. Develop models that leverage real-time data for proactive risk identification and mitigation.
6. Human-Centric IIoT Design:
   - Investigate the human aspects of IIoT implementation in supply chain management. This includes studying the impact of IIoT on the workforce, training requirements, and human-machine collaboration to ensure that technology adoption aligns with social sustainability goals.
7. Performance Benchmarking:

  - Establish benchmarks and performance metrics for evaluating blockchain solutions in IIoT and supply chain contexts.
  - Conduct comparative studies to assess the performance of different blockchain implementations.
8. Cross-Organizational Collaboration:
  - Explore ways in which IIoT can facilitate collaboration among different organizations within a supply chain. This involves the development of interoperable systems and standards that enable seamless information sharing while respecting data privacy and security.
9. Smart Contracts and Automation:
  - Enhance the functionality and reliability of smart contracts to automate complex supply chain processes.
  - Research ways to ensure the correct execution and legal enforceability of smart contracts in various jurisdictions.
10. Regulatory and Ethical Considerations:
  - Examine the regulatory landscape and ethical considerations surrounding the use of IIoT in sustainable supply chain management. Develop guidelines and best practices for ensuring compliance with existing regulations and addressing ethical concerns related to data privacy, security, and environmental impact.
11. Life Cycle Assessment (LCA) Integration:
  - Investigate how IIoT can enhance life cycle assessment methodologies, providing real-time data for a more accurate evaluation of the environmental impact of products and processes throughout their life cycle.
12. Scalability and Standardization:
  - Address challenges related to the scalability of IIoT solutions in diverse industrial settings. Explore the development of standardized frameworks and protocols that enable interoperability and easy adoption across different industries and supply chain ecosystems.

By addressing these research directions, scholars and practitioners can contribute to the development of sustainable, efficient, and resilient supply chains in the era of Industry 4.0.

CRediT authorship contribution statement

Mohsen Soori: Writing – original draft, Funding acquisition, Data curation. **Fooad Karimi Ghaleh Jough:** Project administration, Funding acquisition, Formal analysis, Data curation. **Roza Dastres:** Resources, Methodology, Funding acquisition, Conceptualization. **Behrooz Arezoo:** Supervision, Software, Investigation.

Declaration of competing interest

There is no conflict of interest regarding the submitted manuscript to the Sustainable Manufacturing and Service Economics Journal.

Data availability

Data will be made available on request.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.smse.2024.100026.

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