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Enhancing Supply Chain Traceability through Blockchain and IoT Integration: A Comprehensive Review

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ABSTRACT: Supply chain traceability is essential for ensuring safety, preventing counterfeit goods, and improving efficiency. The integration of blockchain technology and the Internet of Things (IoT) has emerged as a transformative approach to enhance supply chain traceability by creating a secure, transparent, and efficient way to track the movement of goods and materials. This comprehensive literature review examines how the integration of blockchain and the Internet of Things can enhance supply chain traceability, utilizing a systematic literature search to identify and analyze all relevant studies. Recent and related articles selected from the Scopus database were reviewed. Our analysis underscores the potential for blockchain and IoT integration to provide end-to-end visibility, secure data sharing, and real-time monitoring across the supply chain ecosystem. It also identifies Machine Learning (ML) as another key component that enhances the security challenges of the Internet of Things while simultaneously serving as an analytical tool in Supply Chain Management (SCM). The review concludes that the integration of blockchain, the Internet of Things, and ML has the potential to transform supply chain traceability. By providing a secure, transparent, and efficient way to track the movement of goods and materials, businesses can improve their operations and offer better products and services to their customers. However, these findings do not impact the results of this research work. Additional research and a more extensive examination of the literature could offer a more comprehensive insight into the subject matter.

KEYWORDS: Supply chain; supply chain management; blockchain; machine learning; traceability

1. Introduction

Supply chains (SC) are essential for manufacturing and service operations, functioning as systems that move raw materials, goods, and information from suppliers to customers [1]. Supply chain management (SCM) is a strategic approach to managing these systems, involving planning, organizing, and controlling the flow of resources from the beginning to the end of the SC [2]. SCM encompasses a network of entities that move materials through defined steps to deliver products to end customers. This network includes manufacturers, product experts, wholesalers, retail carriers, transportation companies, regulatory agencies, and members of production organizations [3]. SCM covers the management of all aspects of product flow, from raw materials to the final products delivered to the customer. A SC is a value-building activity embedded in the production-distribution practice that includes the explicit organization of relationships among these activities to guarantee efficient delivery of quality and value to the final consumer. It entails the connections from a company's suppliers to the manufacturing and distribution of a specific product or service [4].

Traditional SCM systems face challenges related to traceability, responsiveness to unexpected events, cost control, partner trust, and outdated technologies [5]. In today's increasingly intricate and uncertain SC environments, adaptive planning, control, and transparency are of utmost importance. These strategies ensure the smooth delivery of products to end customers transparently, minimize delays and interruptions, avoid unnecessary costs, and maintain business continuity [3]. The major concern in the SC research community is how to ensure seamless flows of products, information, and financial resources through the chain [6]. Essentially, SC consists of three major flows: material flow, information flow, and cash flow. Efficient management of these activities requires appropriate information flows [7]. It is argued that the performance of SC is highly dependent on the level of trusted relationships that exist between the players in the SC ecosystem [8, 9]. Fortunately, the integration of blockchain technology and the Internet of Things (IoT) undoubtedly presents an opportunity to ameliorate the trust issue.

In today's SC landscape, challenges such as security risks, transparency issues, the possibility of product tampering, counterfeit items, increased administrative burdens, elevated operational expenses, and extended delivery timelines are common when moving goods from producers to end consumers [10]. Blockchain, a disruptive technology altering customary business practices, has become a widespread phenomenon in recent times with overbearing consequences [11]. What makes blockchain a novel technology are its unique features: high transparency, computational logic, decentralized peer-to-peer transactions with no central party, and immutability [12]. Blockchain was introduced in 2008 as the technology driving the Bitcoin digital currency promoted by an anonymous programmer with the pseudonym of Satoshi Nakamoto. The initial apprehension and pessimism against Bitcoins as a new currency disappeared when a boom occurred in 2013, causing the value of one Bitcoin to rise from 13.96 USD to 979.45 USD, representing a price increase of 6900% within a year. This unprecedented price gain has thrust Bitcoins into the limelight, with researchers and industry players actively involved in unraveling the uniqueness of the currency and how to harness the technology behind Bitcoins in other domains [12,13].

Blockchain is promising in solving recent concerns in SCM [14]. The world’s largest SC company, Maersk, pioneered the use of blockchain in international logistics aimed at cost reductions measured through a considerable reduction of paperwork in shipping and container tracking [15]. The ability of blockchain to facilitate a secure exchange of data in a distributed mode has impacted the way organizations are administered and how interrelationships are designed and transactions are executed among SC partners. The integration of blockchain with other technologies such as the Internet-of-Things (IoT) could build an everlasting, distributable, executable record at any instant of a product’s voyage throughout the SC, resulting in the creation of efficiencies all over the worldwide economy. Product traceability, legitimacy, and authenticity are the immediate benefits of the improved visibility expedited by such technology integration.

In modern-day SCM, IoT technology is widely used for tracking and monitoring processes in the SC [16], employing IoT devices such as image sensors, temperature and humidity sensors, GPS trackers, barcode readers, and Radio Frequency Identification (RFID), among others. This real-time data collection helps fleet managers improve the operational efficiency of distribution [17]. Using sensors and software to calculate specific elements of the SC, IoT devices can validate products, streamline the transportation of goods, and track estimated arrival times [16]. IoT provides real-time shipment and inventory visibility, making it easier to analyze big data. Furthermore, it ensures transparency, traceability, and security to enhance the execution and performance of SCM methodology [18]. However, the high risk of cyber threats and attacks IoT is exposed to constitutes a challenge to its use in SC [19]. Inherently, artificial intelligence (AI), especially machine and deep learning, is being promoted as an effective measure to ensure a secure IoT ecosystem [20].

AI has been a key driver of the 4.0 Industrial Revolution (4IR) and is widely employed in the development of intelligent systems, such as machine learning (ML), for implementing security systems against cyber threats and attacks [20]. The deployment of AI in IoT ecosystems as a security measure has been gaining traction in recent years. IoT technology is one of the pillars of 4IR that supports enhancing performance and cost reduction [21]. However, IoTs are vulnerable to cyberattacks due to a combination of their multiple attack surfaces and their newness, thus lacking security standardizations and requirements [22]. AI is a promising approach that can enhance cybersecurity in IoT ecosystems [20]. It can be used to detect unusual behavior that may indicate an attack is occurring [22]. A comparative study of different AI categories and their applicability in IoT security has been performed, recommending that the most convenient and effective AI techniques for mitigating IoT security challenges are advanced analytics and ML [21].

ML is deployed in IoT to combat security vulnerabilities, enabling anomaly detection, predictive maintenance, and real-time threat analysis in IoT networks. Likewise, blockchain is employed in SCM to ensure transparency and tracking of consignments, providing an immutable and decentralized ledger for recording every transaction in the supply chain. This makes it difficult for any party to manipulate or alter data, enhancing transparency and trust among supply chain participants. The integration of blockchain, IoT, and ML technologies presents a compelling opportunity to address the shortcomings of traditional SC traceability systems. This comprehensive review aims to explore the synergistic potential of blockchain, IoT, and ML technologies in enhancing SC traceability, shedding light on the pivotal role they play in reshaping the landscape of SCM. Furthermore, this review will analyze the key benefits and challenges associated with this convergence, examining real-world use cases that highlight the transformative impact on SC.

2. Literature Review

The intricate and multifaceted interrelationship between blockchain, the IoT, and ML in the context of SC has sparked the curiosity of numerous academic researchers. These researchers are driven by distinct approaches and areas of focus within this dynamic intersection of technologies. Blockchain, IoT, and ML offer a vast landscape of possibilities in SCM. Blockchain enhances transparency and trust, IoT provides real-time data from a multitude of sensors, and ML enables data analysis, predictive insights, and anomaly detection [23]. The combination of these technologies creates a fertile ground for innovation and research. Researchers are delving into a wide array of topics, such as the development of secure and transparent SC platforms, optimizing logistics with real-time data analysis, and enhancing security through predictive maintenance and anomaly detection. In essence, the academic community's interest in the interplay between these technologies reflects the recognition of their potential to revolutionize SCM, and diverse research pursuits aim to unlock the full spectrum of opportunities and challenges presented by this convergence [24].

The competitive pressure on companies to efficiently manage their SC activities to sustain their competitive position in an increasingly dynamic business environment has led to the adoption and integration of several technologies, prominent of which is IoT [16, 25]. The advent of wireless technology that birthed IoT and its subsequent assumption of a critical role as a gateway to operational excellence in SCM [16] has motivated researchers' interest in exploring the potential of IoT to improve the exchange of information and to facilitate the monitoring of physical goods throughout the SC [26], resulting in a surge of studies addressing innovative applications in SCM [27, 28].

Previous studies investigated that the use of IoT-based RFID technology in SCM traceability to ensure food safety [29, 20]. They stated that IoT is employed mainly to monitor food safety parameters like temperature, humidity, frozen level, and location. RFID technology has been the subject of extensive research in the context of SC traceability. Several scholars [30–36] have investigated the potential benefits of RFID implementation, including increased visibility, tracking, and communication throughout the SC. Ensuring traceability in the food industry is essential for meeting consumer demands for quality and safe food products. Researchers [37] and [38] have shown how IoT can be used to increase traceability capability in SCM in helping firms achieve this goal. IoT devices can affirm the authenticity of a product while also enabling scrutiny of its origin and quality. Furthermore, these IoT devices offer the assurance of real-time tracking, visibility, and traceability throughout the entire SC. Recent research findings reveal that Australian retailers have integrated IoT devices into their SC processes, including internet-connected barcode technology, sensors and scanners, handheld tablets and smart devices, smartphones, mobile applications, GPS-based location awareness, and web-based security and surveillance systems [39].

The substantial data output generated by IoT devices in SC operations is conventionally stored in the cloud. However, pervasive concerns about privacy and security persist due to the susceptibility associated with centralized data storage, and there is a need for ongoing risk mitigation [24, 39]. IoT devices generate critical and sensitive data, making security threats and automated attacks a growing concern. Many IoT endpoints operate with limited computational capabilities, which traditional security protocols do not support due to anticipated computational complexity. Blockchain can enhance IoT security by providing a decentralized setting, as indicated [40].

Blockchain is an openly accessible report that records completed transactions in blocks. As new blocks are added or expanded, the blockchain's chain of blocks grows longer. Public key cryptography and distributed consensus mechanisms ensure the security and integrity of data such as IoT data. Additionally, various blockchain advancements, such as decentralization, anonymity, persistence, and scalability, enhance data security [41]. Traditional IoT strategies are susceptible to safety and security threats, while collaborative planning for handling sensitive data introduces validation possibilities [42]. Instances of unauthorized access, illicit use, and data breaches have occurred. Achieving extensive adoption of IoT in applications seems challenging. However, blockchain development is anticipated to play a leading role in IoT solution development. The reliability and infinite nature of blockchain can address security vulnerabilities in IoT, and its decentralized nature can secure data and devices in SC operations [4, 43].

Blockchain holds promise for addressing security shortcomings, enhancing data integrity, and transforming transaction processes into permanent, transparent, and decentralized structures. Hence, future work should focus on developing security standards for blockchain-based systems to promote its wider adoption in other technologies such as IoT and SC [44]. Overall, IoT devices have limited computational capabilities and significant security vulnerabilities and are highly susceptible to digital attacks. Traditional IoT systems collect sensitive personal data about their owners, partially managed by organizations, posing serious data integrity and security challenges. Blockchain operates a distributed ledger where nodes reach a consensus without third-party intervention, reducing single points of failure and reliance on third parties [45]. The physical arrangement of IoT devices makes them vulnerable to attacks, potentially altering the transmitted information across these networks. Authentication of devices and initial data integration are crucial concerns [46].

The IoT economy has started deploying sensors and devices for financial transactions, especially in trustless scenarios such as Machine-to-Machine (M2M) and Peer-to-Peer (P2P). With the advancement of 5G, electronic transactions are becoming more prevalent, offering potential solutions for billing and distribution. Blockchain, as a Distributed Ledger Technology (DLT), employs a decentralized framework to facilitate secure and immutable transactions. Blockchains have the potential to revolutionize IoT payments, although several challenges need to be addressed [47]. IoT technology has become an integral part of people's daily lives, enabling real-time monitoring and control of various processes. Smart devices have transformed how individuals interact with their environment. Despite its potential, IoT faces numerous challenges and shortcomings that require innovative solutions. Blockchain technology offers multifaceted approaches and decentralized architectures that can address many of the issues plaguing IoT. Nevertheless, adopting blockchain for IoT will necessitate overcoming computational complexities, reducing delays, and improving processing speed [48–50].

Prominent issues affecting blockchain and the Internet of Things (IoT) include the heavy resource consumption of encrypted node data, centralized architectures leading to single points of failure, device synchronization, management of generated data volume, IoT compatibility, and blockchain technologies [51]. However, storing sensor data on the blockchain through transactions may require fewer resources for security due to the blockchain's inherent data protection capabilities. Theoretically, blockchain-based systems are less vulnerable to threats due to their shared record approach for data protection [52]. Some researchers have focused on intelligent arrangements and emphasized the potential of integrating intelligent contracts into the IoT framework, which could bring about innovative solutions and enhance current operational processes. Specific use cases and development trends in existing IoT blockchain solutions have also been explored in various studies, providing insights into aspects like system design, cryptographic algorithms, and message time-stamping within existing solutions [53−57]. Traditional challenges in IoT data quality have not been entirely resolved by incorporating blockchain into SC. Some argue that blockchain data could be immutable garbage [58]. In response, certain studies have presented two solutions to enhance data integrity and trust in blockchain-enabled IoT food supply chains [59]. These solutions aim to minimize the potential for arbitrary claims regarding IoT data performance and promote supply chain behaviors that increase the likelihood of achieving desirable future states through mechanism design such as incorporating ML into the blockchain-IoT framework [4, 60−64]. Our proposed study constitutes a comprehensive literature review, incorporating an analysis of the progress made in blockchain-based IoT and its current application areas within SCM systems.

3. Materials and Methods

The methodological approach was designed to ensure a rigorous and focused examination of the literature, providing meaningful insights into the integration of blockchain and IoT in supply chain traceability. The study utilized Scopus as the primary database for a systematic literature review, employing a comprehensive set of keywords and Boolean operators to identify relevant articles published in English from 2020 onwards. Initial screening based on titles and abstracts was conducted to exclude duplicates and articles not meeting inclusion criteria. The remaining articles underwent a full-text review to assess their suitability for the study. Exclusion criteria were applied to articles that did not provide substantial information regarding the integration of blockchain, ML, and IoT for SC traceability. Relevant data, including key findings, methodologies, and primary contributions, were extracted from the selected articles. Thematic analysis was performed to identify common themes and emerging trends, which were documented and synthesized in the comprehensive review.

4. Related Work

In this section, selected studies related to this research were reviewed and organized into four subsections. The first part focuses on the application of IoT in SCM, followed by a section on blockchain in SCM. The third and fourth parts discuss ML in SCM and the integration of IoT, blockchain, and ML in SCM, respectively.

4.1. Internet of things in supply chain management.

SCM plays a pivotal role in ensuring the efficient flow of products and materials from suppliers to end consumers. In recent years, the integration of IoT technologies has revolutionized SCM by providing enhanced traceability and real-time monitoring capabilities. IoT technologies enable improved traceability throughout the supply chain [65]. Author [66] emphasizes that IoT sensors and devices can monitor the location, condition, and quality of goods in transit, allowing for enhanced real-time visibility. In the same vein, [67] underscores the ability of IoT to improve quality control and compliance in SCM. IoT sensors can monitor environmental conditions during the transportation of goods, ensuring that they meet specified quality standards and comply with regulatory requirements.

Previous study discuss how IoT-enabled SCM systems can collect data from various points in the supply chain and apply analytics to optimize processes, reduce costs, and improve overall efficiency. The implementation of IoT in SCM also comes with challenges [68]. Other studies highlight issues related to data security and privacy, as well as the need for standardized protocols and interoperability between various IoT devices and platforms. Incorporating IoT in SCM is not limited to traceability but extends to sustainability. IoT-enabled supply chains can reduce environmental impact by optimizing routes, reducing fuel consumption, and minimizing waste [69, 70]. In the study by [71], 14 drivers of IoT adoption in SCM were identified from an extensive literature review on previous IoT and SCM-related works. The most important drivers were analyzed according to their comparative importance based on expert opinions from industrial and academic backgrounds. The results show that "Efficient logistics systems," "Business knowledge acumen," and "Information safety assurance" are among the three most predominant driving factors. Table 1 presents recent research on the application of IoT in SCM as it relates to traceability.

Table 1. Application of IoT in SCM.

Domain	Issues	IoT Technology	Focus
Supply Chain Management [66]	Enhanced traceability, real-time visibility	IoT sensors and devices	Traceability and real-time monitoring in SCM
Quality Control, Logistics [67]	Quality control, compliance, environmental conditions monitoring	IoT sensors and data analysis	Quality control and compliance in logistics
Supply Chain Management [71]	Adoption of IoT	RFID	Identify and investigate drivers of IoT adoption in SCM
Industry 4.0 [68]	Data-driven decision support, optimization, cost reduction	Various IoT devices and data analytics tools	Data-driven decision support in Industry 4.0
Supply Chain Operations [69]	Data security, privacy, standardization, interoperability	Various IoT devices and platforms	Application of IoT in supply chain operations
Sustainable Supply Chain Management [70]	Environmental impact, optimization, sustainability	IoT devices and data analysis for sustainability	Sustainability in supply chain management

As evident from Table 1, the application of IoT in SCM for traceability is a promising area of research, offering enhanced visibility, improved quality control, sustainability, and real-time decision support [66−68, 70]. However, challenges related to security, standardization, and interoperability must be addressed [69]. Future research should focus on the evolving landscape of IoT technologies and their impact on SCM, considering the latest developments.

4.2. Blockchain in supply chain.

Centralized SCM systems are tedious and expensive to maintain, lacking adequate features for collaboration, market analysis, and product authentication [72]. Blockchain has emerged as a solution to address SCM challenges across various industries [59], owing to its efficiency in tackling these issues. The authors propose the adoption of blockchain in SCM to enhance traceability, transparency, security, and fraud prevention. Blockchain is already being successfully used to address SCM challenges in various industries. For instance, blockchain-based product traceability systems can track the movement of goods through the supply chain in real time, preventing counterfeiting and fraud [59]. Studies have demonstrated the use of blockchain to build trust between third parties in different industries, achieved through smart contracts and decentralized off-chain storage for efficient product tracking in the supply chain [73].

The integration of blockchain with the Internet of Things (IoT) is explored by [74]. The combination of IoT and blockchain offers a tamper-proof ledger that records every event in the supply chain, making it nearly impossible to alter data and thereby improving trust and traceability. Real-time data generated by IoT devices can be analyzed to make data-driven decisions. A blockchain-based SCM for ensuring drug traceability and transparency in a medical supply chain system, aimed at creating trust between stakeholders and consumers, was proposed by [75]. The proposed blockchain medical supply chain was developed using an

Ethereum smart contract, and the authors also created a DApp (Decentralized Application) for tracking the medical supply chain. [76] suggests using permissioned blockchain with relevant processes and functions to obtain a holistic framework for securing SCM. The framework employs ERC20 standards to implement smart contracts. A case study demonstrated the efficacy of the proposed framework, overcoming critical deficiencies in the current supply chain. The summary of the application of blockchain in SCM is enumerated in Table 2.

Table 2. Application of Blockchain in SCM.

Domain	Issues	Blockchain Type	Focus
Supply Chain Management [59]	Tedious and expensive to maintain	Blockchain	Efficiency, transparency, security
Supply Chain Management [73]	Build trust between third parties	Blockchain	Product traceability, efficiency
Medical supply chain [75]	Create trust between stakeholders and consumers	Blockchain	Product traceability, transparency
Supply Chain Management [76]	Overcome critical deficiencies in the current supply chain	Permissioned blockchain	Efficiency, security, transparency
Supply Chain Management, Blockchain [74]	Data security, traceability, trust	IoT devices and blockchain integration	Traceability and trust in supply chain with blockchain

As evident in Table 2, blockchain technology is emerging as a promising solution to the key challenges of SCM, including traceability, transparency, security, and fraud prevention [59, 73, 76]. Blockchain can track the movement of goods through the supply chain in real-time, create a tamper-proof record of all transactions, and protect sensitive data [74]. Additionally, it can be integrated with other technologies, such as IoT, to further improve the efficiency and security of SCM [75].

4.3 Machine learning in supply chain management.

The rapid proliferation of IoT devices, in various forms and sizes, results in an upsurge of data, consequently leading to cybersecurity challenges [77]. The identification and control of these cybersecurity risks emerge as a key emphasis within the IoT sphere. ML methods are widely recognized as among the most promising means to tackle and guarantee robust cybersecurity against threats. ML techniques are of utmost importance across a spectrum of cybersecurity applications [78]. Previous study [79] have identified various types of IoT threats and discussed shallow and deep ML-based intrusion detection systems (IDS) in the IoT environment. The performance of these models has been evaluated using five benchmark datasets such as NSL-KDD, IoTDevNet, DS2OS, IoTID20, and IoT Botnet dataset. Various performance metrics such as accuracy, precision, recall, and F1-score were used to evaluate the performance of shallow and deep ML-based IDS. The authors found that deep ML IDS outperforms shallow ML in detecting IoT attacks.

Another study [80] exploited the waveform superposition property of a multi-access channel to develop an over-the-air computation-based communication-efficient federated ML framework for intelligent IoT networks. The reconfigurable intelligent surface is further leveraged to reduce the model aggregation error by enhancing the signal strength through reconfiguration of the wireless propagation environments. An innovative method that combines evolutionary and deep learning techniques to identify cyber-attacks in a cloud-based SCM environment was investigated [81]. The input data is preprocessed to make it suitable, while Evolution Social Spider Optimization (ESSO) was used to streamline high-dimensional data and select key features. A Deep Belief Network (DBN) trained by an Extreme Learning Machine (ELM) is then used to detect and classify cyber-attacks. Further performance enhancement is achieved through the application of Poor and Rich Optimization (PRO) algorithms. This PRO-optimized ELM-trained DBN model is designed to bolster security in SCM by recognizing and classifying intrusions. Experimental results on benchmark datasets show that this approach, particularly in the Blockchain of Things-Internet of Things (BoT-IoT) dataset, achieves an impressive average accuracy of 99%, while the Modbus dataset reaches 99.5%, surpassing recent methods.

ML approach for network anomaly detection and constructing data-driven models to detect Distributed Denial of Service (DDoS) attacks on Industry 4.0 Cyber-Physical Systems (CPSs). Limitations of existing techniques, such as artificial data and small datasets, are addressed by capturing network traffic data from a real-world semiconductor production factory. Forty-five bidirectional network flow features are extracted, and labeled datasets are constructed for training and testing ML models. The proposed PCA-BSO algorithm is employed to select the most relevant features based on their eigenvalues, as the feature with the highest eigenvalues may not always improve classification accuracy. Supervised ML algorithms are evaluated through simulations to assess their performance [82].

A study by [83] identifies a potential issue with existing research on predicting shipping risks during natural disasters. To address this issue, the review proposes a novel hybrid deep learning approach, combining CNN and BiGRU. The proposed approach achieves an impressive accuracy improvement of up to 94% when compared to baseline models, suggesting that it has the potential to significantly improve shipping risk prediction during natural disasters. The summary of research related to the application of ML in IoT-enabled SCM is offered in Table 3.

Table 3. Application of Machine Learning in SCM.

Domain	Issues	Machine Learning Algorithm	Focus
IoT [79]	Security	Decision Tree, Random Forest, Support Vector Machine, Deep Neural Network, Deep Belief Network, Long Short-Term Memory, Stacked LSTM, Bidirectional LSTM	Intrusion Detection Systems (IDS)
IoT [80]	Communication Bandwidth	Federated Machine Learning	Efficient Federated ML Framework
IoT [81]	Cyber-attacks	Deep Belief Network (DBN), Extreme Learning Machine (ELM), Evolution Social Spider Optimization (ESSO	Cyber-attacks Detection in SCM
Industry 4.0 CPSs [82]	Cybersecurity	Machine Learning	Network Anomaly DDoS Attack Detection
Logistics [83]	Predicting risks in shipping operations during natural disasters	Hybrid deep learning (DL) approach, convolutional neural network (CNN) + bidirectional gating recurrent unit (BiGRU)	Reducing the impact of natural disasters on shipping operations

As shown in Table 3, some different reasons and domains utilize ML techniques to address either security, analytical, or efficiency issues. As shown in Table 3, ML is used in IoT either for security or for analytical/prediction purposes. Predominantly, ML is used for security purposes based on the research considered [79−82]. The other used for ML is IoT-SCM for analytical or prediction purposes as demonstrated in [83]. Several ML algorithm tools employed include Decision Tree, Random Forest, Support Vector Machine, Deep Neural Network, Deep Belief Network, Long Short-Term Memory, Stacked LSTM, and Bidirectional LSTM. However, Deep Learning algorithms such as DBN and CNN are shown to perform better than shallow learning algorithms [80]. These research efforts underscore the growing importance of ML in enhancing IoT and cybersecurity.

4.4. Integration of IoT, ML, and Blockchain in SCM.

The combination of blockchain, IoT, and ML in SCM is a strategic approach that addresses the inherent weaknesses of each technology while leveraging their strengths [84]. Concerned about the issues of illegal activities facing the fish industry within its traditional SC, [85] proposed an integration of blockchain and IoT technologies to transform the industry, aiming to create transparent and secure traceability systems to combat these issues. To achieve this goal, the authors designed an intelligent framework that uses distributed ledger technology to track fish products from harvesting to delivery, providing valuable information for verification. In a unique approach, they also explored the integration of ML for assessing fish quality, freshness, and fraud detection within these systems.

Motivated by the desire to ensure food safety from farm to fork, previous study proposed the combination of digital technologies such as blockchain, IoT, and ML to ensure the traceability of food products throughout the agricultural SC. This can help improve consumer confidence and support sustainable agriculture. The authors argued that digital transformation along the SC can be achieved through: (1) the implementation and improvement of traceability systems using blockchain technology, and (2) the integration of blockchain with smart and rapid tests or IoT using AI to enhance blockchain intelligence [86].

Drug supply chain management (DSCM) is a vital procedure for pharmaceutical industries as it ensures that medicines are delivered securely and effectively to patients. Effectual DSCM comprises the coordination and management of many key actions like warehousing, drug manufacturing, transportation, and distribution. To improve DSCM, pharmaceutical companies leverage technologies such as blockchain, IoT, and AI to enhance traceability, increase inventory management, and improve communication and collaboration between stakeholders. These serve as motivation for [87] to work on the design of a Blockchain Assisted Archimedes Optimization with ML Driven Drug Supply Management (BAOML-DSM) technique for the Pharmaceutical Sector. The presented BAOML-DSM technique focuses on the recommendation of drugs in the pharmaceutical sector.

Previous study [88] explored how IoT and blockchain technology might be used to enhance the SC process by making it more resilient and dependable, especially considering the experience of the recent pandemic that highlighted the importance of SC systems less dependent on humans and more efficient in cycling goods in SC. They observed that the firm's competition has shifted to SC and that the firm with a competitive advantage in SC wins the race by employing technologies that facilitate real-time traceability of products and merchandise while they are moving through the value chain network. It was argued that applications of IoT and blockchain facilitate observation, tracking, and monitoring of products, activities, privacy, security, and processes within SC networks. The authors demonstrated that the combination of IoT, blockchain, and ML can increase the effectiveness and efficiency of modern SC, while also being helpful for the sustainable development of social, economic, and environmental contexts. Another study investigated that the adoption of blockchain in managing complex global SC. The study argued that aside from the established SC performance criteria, Industry 4.0 requirements of a more data-driven SC, whereby data collection, transmission, and processing capabilities are embedded in smart products, place more stringent requirements on modern SC. This article reveals that the three most often researched topics related to blockchain SC are transparency/traceability, transaction-related issues, and tracking [89]. Table 4 is a summary of reviewed works related to the integration of blockchain, IoT, and ML in SC.

Table 4. Integration of Blockchain, IoT, and ML in SCM.

Domain	Issues	Combined Technologies	Focus
Fish Supply Chain [85]	IUU Activities, Traceability	Machine Learning, Blockchain, IoT	Deep Learning to build trustworthy, transparent, decentralized traceability and Intrusion Detection Systems
Agriculture [86]	Traceability and Transparency	Machine Learning, Blockchain, IoT	Implementation and Improvement of Traceability Systems using Blockchain Technology and Integration with Smart and Rapid Tests or IoT using AI to Enhance Blockchain Intelligence
Pharmaceutical Industry [87]	Drug Supply Chain Management	Machine Learning, Blockchain, IoT	Blockchain Assisted Archimedes Optimization with Machine Learning Driven Drug Supply Management (BAOML-DSM) Technique for Pharmaceutical Sector
Supply Chain Management [88]	Traceability and Transparency	Machine Learning, Blockchain, IoT	Improving SC Procedures with IoT and Blockchain Technology
Supply Chain Management [89]	Transparency/Traceability, Transaction Related Issues, Tracking	Machine Learning, Blockchain	Role of Blockchain in SC and Methodology to Study Co-Occurrence of Blockchain Topics in SC

Table 4 summarizes literature that explores the integration of blockchain, IoT, and ML across various SC contexts. It addresses the need for transparent and secure traceability systems in the fish industry and agriculture, advocating for the adoption of digital technologies to ensure food safety, consumer confidence, and sustainability [85, 86]. The pharmaceutical sector leverages these technologies to enhance drug supply chain management, emphasizing traceability, inventory management, and stakeholder communication [87]. Resilience and efficiency in supply chains, particularly in the context of global challenges, are underlined, with IoT and blockchain technology enabling real-time traceability and efficiency improvements [88]. The review also highlights common research themes, including transparency, traceability, transaction-related issues, and tracking, reflecting the growing interest in leveraging these digital technologies to enhance supply chain management [89].

5. Discussion

The integration of IoT, blockchain, and ML presents a promising frontier in SCM. This discussion delves into key points from the reviewed articles, highlighting implications and potential avenues for future research in this evolving field. IoT is applied in SCM to enhance traceability, real-time monitoring, and visibility into the movement of goods [66, 67, 70]. Its implementation has reduced costs, strengthened quality control, and supported sustainability efforts within the supply chain [68]. However, issues related to security, standardization, and interoperability must be carefully addressed to ensure seamless integration [69].

Blockchain adoption in SCM is driven by its ability to offer a secure, transparent, and tamper-proof record of all transactions [59, 73, 76], particularly valuable for traceability, transparency, security, and fraud prevention in the supply chain [74]. Moreover, blockchain can be seamlessly integrated with IoT, further enhancing the efficiency and security of SCM [75]. In the course of the review, it was discovered that ML is being employed in IoT-SCM for both security and analytical purposes. ML techniques are predominantly used for enhancing security within IoT systems [79−81], including the use of various ML algorithms such as Decision Trees, Random Forest, Support Vector Machines, Deep Neural Networks, and more [81, 82]. Notably, deep learning algorithms, like Deep Belief Networks (DBN) and Convolutional Neural Networks (CNN), have demonstrated superior performance in addressing security concerns [83].

Synergy is the principle that the whole is greater than the sum of its parts. In the context of SCM, the integration of blockchain, IoT, and ML creates a system that is more than just the sum of the capabilities of each individual technology [84]. It has broad applications across various supply chain contexts. For instance, in the fish industry and agriculture, these technologies are championed to ensure food safety, build consumer confidence, and promote sustainability [85, 86]. Similarly, the pharmaceutical sector leverages these technologies to enhance drug supply chain management, focusing on traceability, inventory management, and stakeholder communication [90]. The ongoing global challenges underscore the need for resilient and efficient supply chains. IoT and blockchain technology offer the capability for real-time traceability and efficiency improvements, addressing critical issues in the SCM field. The literature review emphasizes recurring research themes, such as transparency, traceability, transaction-related issues, and tracking, reflecting the increasing interest in leveraging digital technologies, including blockchain, IoT, and ML, to optimize SCM [88, 89]

4. Conclusions

this review highlights the transformative potential of integrating IoT, blockchain, and ML in SCM. The amalgamation of these technologies offers remarkable enhancements in transparency, security, and efficiency across diverse industries. The synergy of IoT enables real-time data acquisition, blockchain ensures a secure and immutable ledger, and ML empowers intelligent decision-making. However, the adoption of these technologies is not without challenges, encompassing technological complexities, organizational adjustments, and regulatory considerations. Systematic efforts are imperative to address these challenges and fully harness the benefits. Continuous exploration of evolving technologies and adaptive practices within SCM is essential for staying ahead in an ever-changing landscape. Ongoing research efforts play a pivotal role in shaping the future of SCM, steering it towards meeting the dynamic demands of an interconnected world. As industries embrace the amalgamation of IoT, blockchain, and ML, the transformative journey towards a more transparent, secure, and efficient global supply chain relies on proactive problem-solving, innovation, and a commitment to staying abreast of emerging trends.

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Conflict of Interest

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