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Research Article

Blockchain and AI Integration in Supply Chain Management: Transforming Transparency, Security, and Efficiency in Material Flow Systems

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Abstract

Background: Over the last few years, blockchain and artificial intelligence (AI) applications in supply chain management (SCM) have become a transformational solution to increase transparency, security, and efficiency. Conventional supply chain systems are associated with inefficiencies, information silos, faddiness, and deficiency of traceability, which greatly impede efficiency. The synergies of a decentralized and safe data format of blockchain and predictive performance of AI have the chance to resolve these issues and streamline supply chain processes. **Methods:** The study employed the mixed-methods approach, which included secondary data gathering based on peer-reviewed articles, industry reports, and case studies related to blockchain and AI integration. The study utilizes statistical analysis to investigate current trends and associations and machine learning algorithms are used to examine how blockchain and AI can influence supply chain performance indicators, including demand forecasting, inventory management, and operational effectiveness. The data on different industries such as food, pharmaceuticals and logistics were studied to have a glimpse of the real-world uses of such technologies. **Results:** The findings indicate that blockchain and AI integration have a significant positive impact on transparency as it creates an unalterable and up-to-date version of each transaction and improves operational efficiency since it allows for the optimization of resource distribution, demand forecasting, and inventory control. Blockchain offers verifiable data, which is reassured, and AI can make predictive analytics and automation that can decrease errors and enhance decision-making initiatives within supply chains. **Conclusion:** A combination of blockchain and AI is an exciting option to revolutionize supply chain management. Although other issues such as scalability and system integration are still facing challenges, the benefits of these technologies are enormous in terms of security, transparency and efficiency.

Keywords

Blockchain, Supply Chain Management (SCM), Logistics Management, End-to-End Supply Chain

1. Introduction

Supply chain management (SCM) is a critical element of efficiency and competitiveness of businesses in the contemporary fast changing global market. In spite of being functional, traditional supply chains are often characterized by many issues that include inefficiency, lack of transparency and data silos, fraud and weakness in the process of tracking material movement. Such challenges make organizations less able to effectively respond to changes in the market, risk management, product quality and safety in the complex global chain of supplies (Prado-Prado et al., 2020). As digital

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technologies emerged, however, there is now an opportunity to make substantial improvements in the functioning of a supply chain. However, the most prominent among them is blockchain and artificial intelligence (AI), which has become a revolutionary technology standing a chance to transform the supply chain management (Kashem et al., 2023).

A decentralized and unchangeable digital registry, blockchain is a secure and transparent method of documenting transactions and data within supply chains. Blockchain began its broad use as an initial phenomenon popularized by cryptocurrencies such as Bitcoin, and it has a much wider array of applications. Applied to supply chains, blockchain can be used to track goods and transactions in real-time and in a way that cannot be tampered with by different parties without the use of a centralized authority (Helo &Shamsuzzoha, 2020; Rejeb et al., 2019). The transparency and security are important in the business environment where they aim to improve traceability, control fraud, alleviate risks of counterfeit goods, and especially in the food, pharmaceutical, and luxury goods industries. The blockchain can provide a certain degree of trust which is a fundamental consideration in the supply chain ecosystem by ensuring that all transactions are recorded on a distributed ledger, are verifiable, cannot be changed or deleted (Wu et al., 2017).

Conversely, Artificial Intelligence (AI) has a transformative contribution of equal magnitude since it will allow supply chains to become more intelligent and responsive toward real-time data. AI is the learning, analysis, and decision-making capabilities of machines and systems using big data. Quotient AI tools AI-based supply chain management systems can anticipate supply and demand changes, path optimization, warehouse management, and enhanced inventory utilization with machine learning algorithms (Raja Santhi & Muthuswamy, 2022). AI may use this information to predict the trends in future by reviewing the past trends and making its predictions through learning which can help preclude future problems before they occur. This predictive ability enhances decision making and decreases human error and allows business organizations to run more effectively (A. & R., 2023).

Blockchain and AI in the supply chain management are especially powerful due to the complementation of the two technologies. Blockchain guarantees security, traceability, and transparency of transactions, whereas AI is expected to provide the predictive capacity and decision-making power to optimize the processes and automate them. Combined, the technologies can enable a more resilient and efficient supply chain capable of responding to market demand response in a timely manner, mitigating risks, and lowering operational expenses (Abideen et al., 2021; Aljohani, 2023).

A promising field where blockchain and AI can be utilized is the enhancement of the transparency and safety of material flow systems. There is a high likelihood that traditional supply chains are fraught with information gaps, delays in communication as well as churning of data. Implementing the blockchain technology enables all the stakeholders in the chain to gain access to one inescapable record of transactions, enhance accountability (Agarwal et al., 2022; Taj et al., 2023). In the meantime, AI has the potential to boost the general performance, allowing it to perform automated tasks, predictive analytics, and real-time decision-making. As an example, in the food sector, blockchain can deliver complete farm-to-table traceability, and every product is safely tracked whereas AI can be used to forecast consumer demand, inventory management, and streamline supply chain operations (Verma et al., 2022).

The next important benefit of combining blockchain and AI is the possibility to overcome the inefficiencies of inventory management and logistics. AI-based algorithms may constantly check and examine stock supplies, forecast a deficit or overstocking situation and propose reordering times in accordance with demand anticipations. This is further fostered by blockchain guaranteeing the validity and correctness of data used by AI which indeed facilitates better inventory control and optimization of the supply chain (Kashem et al., 2023; Sani et al., 2024; Wu et al., 2017). Moreover, AI-based analytics can predict possible threats or disruptions in the supply chain, including delivery lags or supplier problems and give practical information to address these threats before they escalate.

Although the potential of the integration of blockchain and AI is promising, there are still difficulties. Scalability of blockchain, which is relevant especially in international supply chains with high transactions, is an issue. Possibly, the main drawback of the traditional blockchain networks is their limitation in terms of speed and energy consumption of transactions which can be a setback to the implementation of the technology on large scale (C. Wang & Zhao, 2023). Also, blockchain is more secure, but has weaknesses, especially when incorporating IoT devices and RFID systems feeding data to the blockchain system. These issues point to a necessity of the ongoing research on increasing the scalability, energy-efficiency and security of blockchain.

Furthermore, the effective application of the blockchain and artificial intelligence in supply chains presupposes that it is necessary to overcome considerable technical, financial, and regulatory challenges. The companies need to invest in infrastructures, consolidate the existing systems and align all supply chain stakeholders (Rehman et al., 2022). The regulatory authorities should also be modified to support the adoption of decentralized technology such as blockchain and Artificial Intelligence, especially when it comes to data privacy or international transactions.

However, the advantages of introducing blockchain and AI into the supply chain management cannot be ignored. These technologies will solve most of the inefficiencies, security

challenges and complications that traditional supply chains are experiencing. Protecting businesses, new opportunities to enhance transparency, efficiency, and responsiveness are available through blockchain and AI that keeps advancing and are likely to find new use in the realm of supply chain management in the future. Over the next few years, these technologies will continue to grow, and the involvement of more academia, industry, and regulation agencies will probably advance the popularity of blockchain and AI-based supply chains, and eventually change the landscape of global trade.

2. Material and Methods

2.1 Research Design

The study design of the research is a mixed-method approach, which combines both quantitative and qualitative research designs to achieve an in-depth understanding of how blockchain and AI can be integrated into the supply chain management. The qualitative component is a detailed case study of the current application of blockchain and AI in supply chains, drawing into the discussion the sphere of food, pharmaceutical, and logistics. Quantitative component of the research is based on statistical and machine learning methods of analysis of data in these systems to evaluate the effectiveness of the integration of blockchain and AI to improve transparency, security, and efficiency of the material flow. Bringing these methods together, the study will give not only theoretical knowledge about the efficiency and obstacles of combining blockchain and AI to real-life supply chains, but also an empirical collection of evidence.

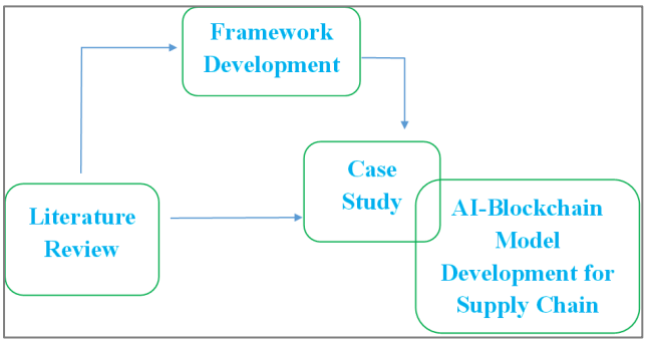

Figure 1. *Research Methodology Framework: The diagram shows the research flow, starting with the Literature Review, followed by Framework Development, Case Study, and ending with AI-Blockchain Model Development for Supply Chain.*

2.2 Data Collection

To conduct secondary data collection, I identified data on peer-reviewed journals, industry reports, and academic papers concerning the integration of blockchain and AI in supply chain management. Such sources were useful in terms of understanding the existing technologies, applications, and challenges in the implementation of blockchain and AI solutions in industries. Information was chosen with references to what the research he did was about, such as case-studies and examples on fields like food, pharmaceuticals and logistics. The data gathered as secondary data aided in developing a theoretical framework of the AI-Blockchain model in supply chains.

2.3 Blockchain Technology in Supply Chain Management

Blockchain Technology in Supply Chain Management plays a transformative role by providing a secure, transparent, and decentralized method of recording transactions and tracking goods across the supply chain. Blockchain makes the information regarding material flow, transactions, and the history of the product irreversible and verifiable in real-time with the help of a distributed ledger. The technology will get rid of the middlemen, which will save money and enhance productivity. Blockchain improves traceability in supply chains, authenticity, fraud prevention and the availability of correct information in a secure way to all stakeholders involved. It is especially useful in such industries as food, pharmaceuticals and luxurious goods, where provenance and security play the key role.

2.4 Artificial Intelligence (AI) in Supply Chain Optimization

Supply Chain Optimization with Artificial Intelligence (AI) involves using sophisticated algorithms and machine learning to enhance decision-making, demand forecasting, and optimization. Using AI will allow businesses to predict the necessary inventory, optimize logistics, and automate manual work based on real-time analysis of vast amounts of data. Analyzing past data and identifying trends, AI can forecast future trends, address the risks in supply chain management, as well as enhance resource allocation. In other industries such as retail, manufacturing and logistics, AI helps to enhance efficiency by cutting down on waste, minimizing delays and customer satisfaction. Its combination with the other technologies like blockchain also increases its capacity of giving transparent data-based insights to allow optimized management of the supply chain.

2.5 Data Analysis

This study used both machine learning algorithms and statistical techniques in its Data Analysis to determine the

effects of blockchain and AI integrations in supply chain efficiency. First, key data points gathered on the secondary sources were summarized with the help of descriptive statistics and identified trends and patterns in the application of blockchain and AI to industries. Then the regression analysis was conducted to determine the relationship among blockchain transparency, AI optimization, and overall supply chain performance. Also, machine learning models were used to forecast the outcome of supply chains like demand forecasting and inventory management, using the past data. The analyses were done using Python and R and the effectiveness of the AI models were measured using performance measures like accuracy, precision and recall.

3. Results

3.1 Publication Trend and Growth

The findings indicate a definite positive trend in the study of the integration of blockchain and AI in supply chain management where the number of publications is steadily growing throughout the researched timeframe and reaching the highest point in 2022 and turning downward in 2023. This trend shows that the subject matters have developed very fast as a nascent field of study into a powerful research stream. The almost equal growths in the number of publications are indicative of growing scholarly concern regarding how blockchain and AI integration can add to material flow systems transparency and data protection and contribute to operational efficiency.

Geographic and authorship analysis also shows that this area of research is globally spread and is driven by a small number of very productive scholars. The greatest number of publications came out of India, then China, then United Kingdom, Italy and the United States, indicating that the developed and other emerging economies are actively contributing to the field. These results indicate that the advances of blockchain-AI-enabled supply chains knowledge base are being established by a focused scholarly leadership and extensive worldwide involvement.

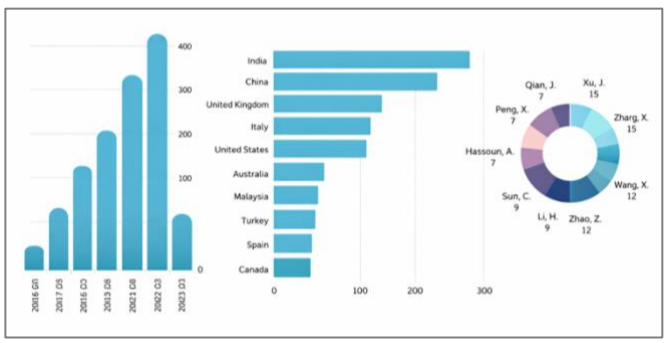

Figure 2. *Publication trends and author distribution in blockchain and AI integration in supply chain management. The bar chart on the left shows the publication count from 2016 to 2023, highlighting a peak in 2022. The horizontal bar chart in the middle represents the top countries contributing to the research, with India leading (Sharma et al., 2023).*

3.2 Technological Integration in Supply Chain Management

The combination of blockchain and AI in the management of supply chains has proven to have a great potential in increasing visibility, safety, and efficiency in the material flow systems. The study indicates a significant rise in the utilization of such technologies in industries with blockchain offering a decentralized and immutable registry that safeguards transactions along with information exchange whereas AI offers smarter decision-making by way of predictive analytics and machine learning. Such blend makes it possible to conduct more accurate tracking, gain a real-time understanding and automate supply chain processes to reduce the number of errors, promote faster decision-making and enhance operational performance.

Moreover, the research shows that blockchain and AI usage is used with other new technologies, e.g. IoT, RFID, and cloud computing to optimize the material flows even more. To illustrate, IoT devices can be used to collect real-time data that is analyzed with an AI algorithm to forecast demand and optimize inventory. In the meantime, blockchain can secure and verify the integrity of the data, eliminating tampering and fraud. Although the advantages are very obvious, there are issues to face, especially when it comes to scalability, energy usage, and system integration. With the field shifting, the solution to these shortcomings will play a crucial role in ensuring the potential of blockchain and AI can be fully realized in revolutionizing supply chain operations.

Table 1. *Overview of Key Technologies in Supply Chain Management: Descriptions, Main Uses, Benefits, and Limitations.*

Technology	Description	Main Uses	Benefits	Limitations
Blockchain	A decentralized digital system for securely storing transactions and data.	Cryptocurrencies, supply chain management, smart contracts, financial systems	Offers transparency, security, and immutability	Faces challenges with scalability, energy usage, storage demands, and regulatory concerns

IoT	A network of interconnected devices and sensors that share data and communicate.	Smart homes, automation in industries, healthcare monitoring	Enhances automation, provides real-time insights, and increases efficiency	Exposes vulnerabilities in security, privacy issues, and difficulties with system integration
RFID	Technology that uses radio waves to identify and track items through tags containing electronic data.	Managing inventory, tracking assets, and controlling access	Improves tracking accuracy, efficiency, and minimizes manual labor	High cost, limited range, and potential interference from other signals
QR Code	A two-dimensional barcode that holds various types of information.	Used for marketing, event ticketing, and payment systems	Easy to scan, versatile, and stores large amounts of data	Has limited data capacity and struggles with scanning in certain environments
Cloud Computing	The delivery of computing resources and services over the internet as needed.	Provides Infrastructure as a Service (IaaS), Platform as a Service (PaaS), and Software as a Service (SaaS)	Offers scalability, reduces costs, and increases accessibility	Poses security risks, vendor dependency, and potential for downtime
Artificial Intelligence	Machines designed to simulate human intelligence for decision-making and autonomous learning.	Applications include natural language processing, image recognition, and recommendation systems	Facilitates automation, improves efficiency, and enables advanced data analysis	Raises ethical concerns, issues with bias, and potential job loss
Big Data	Extremely large and complex data sets requiring specialized methods to process and analyze.	Used in business analysis, predictive modeling, and personalized services	Generates insights, offers a competitive advantage, and supports targeted recommendations	Faces challenges around data privacy, infrastructure, and maintaining data quality
GPS	A satellite-based navigation system that provides location and timing data.	Used for navigation, logistics, and geolocation services	Highly accurate, enables real-time tracking, and is widely accessible	May struggle with signal reception indoors or in remote locations
NFC	A short-range wireless technology that enables contactless data transfers.	Used in mobile payments, access control, and ticketing systems	Convenient, easy to use, and compatible with smartphones	Has a limited range, poses security concerns, and faces adoption hurdles

3.3 Challenges and Opportunities in Integrating Blockchain and AI with Other Technologies

Introduction of the concepts of blockchain and AI into the sphere of supply chain management upgrades the security, scalability and data processing of the material flow systems to a large extent. Decentralized, blockchain provides a high level of protection and guarantees the information is transparent and unchanged, which is instrumental in preserving trustworthy and valid transactions. Decentralization enables the scalability of blockchain as it can effectively support increasing volumes of transactions and overall, the lack of centralization can facilitate interaction between different systems to establish a secure and reliable platform to conduct supply chain activities. In the same way, AI can improve decision-making, handling big data sets, forecasting tendencies, and optimizing logistics, which means the correct management of data provided and the enhanced supply chain and overall transparency in general.

Although blockchain offers the underlying security and scalability of material tracking, AI enhances it, making them more efficient, allowing the analysis of data in real-time and automate the processes. The outcome of such integration is enhanced connectivity to devices and systems, which are supported by IoT and cloud computing. Nonetheless, there are

obstacles, especially in the areas of data protection in the IoT, RFID, and QR codes, which differ based on the implementation, and the weakness to scale of such technologies as QR codes and GPS. Regardless of these challenges, blockchain and AI, when used together, introduce a potentially life-changing solution to incorporate more efficiency and security in the contemporary supply chains.

Table 2. *Comparison of Key Technologies in Supply Chain Management: Security Features, Connectivity, Scalability, and Data Handling.*

Technology	Security features	Connectivity	Scalability	Data handling
Blockchain	Provides strong protection through a decentralized network structure.	Supports interaction across multiple devices and systems.	Adapts well to growing transaction volumes and storage needs.	Preserves transparency and data immutability through distributed ledger records.
IoT	Security levels vary depending on the devices and systems used.	Connects a wide range of devices through different communication protocols.	Can expand efficiently for large-scale implementations.	Supports continuous collection and analysis of real-time data.
RFID	Includes only basic security protections.	Operates through short-range wireless communication.	Can be extended to track numerous items at once.	Handles a limited amount of stored information.
QR code	Does not offer built-in security mechanisms.	Enables access and interaction through code scanning.	Not typically designed for scalability.	Allows quick encoding and retrieval of information.
Cloud computing	Uses comprehensive security controls to protect systems and data.	Depends on internet-based access and communication.	Highly flexible in scaling resources up or down.	Supports remote data storage, management, and processing.
Artificial intelligence	Security depends on how the system is designed and implemented.	Commonly relies on internet-connected platforms and systems.	Can grow effectively to support complex data analysis and computation.	Processes large volumes of data for learning, prediction, and decision-making.
Big data	Security protections differ according to the platform and architecture used.	Often functions through internet-supported infrastructure.	Highly capable of managing expanding and very large datasets.	Enables large-scale storage, processing, and analytical operations.
GPS	Lacks strong built-in security features.	Relies on satellite and positioning-based connectivity.	Scalability is generally not a primary feature.	Effectively captures and manages location-related information.

3.4 Challenges in Scaling and Securing Blockchain-AI Integrated Supply Chain Systems

The combination of blockchain and AI technologies in the sphere of supply chain management has been a subject of thorough research in recent sources, with all of them pointing at the tremendous improvements in supply chain transparency, security, and efficiency. The articles reviewed demonstrate that blockchain-based solutions can offer a decentralized system to guarantee data and transaction security in the diverse industries, such as agriculture and food supply chains. As an example, Ehsan (2022) and Bosona et al. (2023) note that a blockchain helps to increase the level of traceability and security, especially in the sphere of smart farming and in the agricultural supply chain. Together with the Internet of Things (IoT), AI technologies are used to enhance real-time monitoring and decision-making, optimization of logistics and inventory (Bosona&Gebresenbet, 2023; Ehsan et al., 2022). These combined solutions are not only cost efficient but also offer increased accountability and visibility in the material flow systems.

Nevertheless, the scalability, security, and interoperability are some issues associated with the integration of blockchain and AI with other technologies such as RFID, IoT, and QR codes despite their promising outcomes. To illustrate, the Bhatia & Albarrak et al. (2023) and Borandag et al. (2023) studies point out the fact that blockchain and IoT are potentially helpful in enhancing the traceability and safety of the supply chain, yet the size of the organization is one of the challenges encountered when implementing such systems (Bhatia & Albarrak, 2023; Borandag, 2023). Also, the security is maintained at various levels due to different encryption levels and vulnerabilities of gadgets implemented in IoT and RFID systems, as observed in the study by Feng et al. (2020). These challenges are one of the ways that can be used to achieve the potential that blockchain and AI integration can bring to supply chain management.

Table 3. *Summary of Recent Research on Blockchain and AI Integration in Supply Chain Management: Key Findings and*

Technologies Used (Ellahi et al., 2023).

Title of Article/Report /Book	Author	Journal	Year	BC	RFID	IoT	QR	CC	GPS	NFC	BDA	AI
Blockchain-assisted Internet of Things Framework in Smart Livestock Farming	Alshehri, M.	*Internet of Things (The Netherlands)*	2023	X		X					X	X
A Blockchain-Enabled Security Framework for Smart Agriculture	Chatterjee, A., et al.	*Computers and Electrical Engineering*	2023	X		X		X			X	X
Construction of Rice Supply Chain Supervision Model Driven by Blockchain Smart Contract	Peng, W., et al.	*Scientific Reports*	2022	X		X						X
Blockchain-Enabled Supply Chain Platform for Indian Dairy Industry: Safety and Traceability	Khanna, R., et al.	*Foods*	2022	X								X
Agriculture-Food Supply-Chain Management Based on Blockchain and IoT: A Narrative on Enterprise Blockchain Interoperability	Bhat, S., et al.	*Agriculture (Switzerland)*	2022	X		X		X				X
Applying Blockchain Technology to Improve Agri-Food Traceability: A Review of Development Methods, Benefits, and Challenges	Feng, M., et al.	*Journal of Cleaner Production*	2020	X		X		X			X	X

3.5 Automating and Securing Supply Chain Processes with Blockchain and AI

Stakeholders play a crucial role in the process of rolling out blockchain and AI in supply chain management and ensuring that various aspects of the process of material flow become transparent, secure, and efficient. The diagram shown in the figure has indicated a strong architecture in which various stakeholders such as the production businesses, transportation authorities and regulatory institutions mingle effectively with other parties using blockchain technology. Smart contracts allow data interactions between these entities, automating such processes as validation, initializing, and credit assessment, making sure that everything is safe, transparent, and traceable. The sphere of optimizing decision-making, analyzing real-time information and automating the process is one of the areas where AI contributes to improving the entire supply chain ecosystem, improving predictive applications and business operations.

Also, the combination of these technologies helps to organize the complicated processes of the supply chain, as it has been represented in the two operational flows of sales and production. Blockchain is a guarantee of data integrity throughout its transition between different steps, including the stages of acquisition, drying, packaging, and warehousing. The allocation of resources, inventory, and efficiency of the logistics is enhanced with the help of the AI-driven algorithm, and in combination with the secure and transparent data exchange provided by blockchain enables creating a more efficient and reliable supply chain. Nonetheless, the scalability and the issue of interoperability emerge as the major points of concern, as the system utilizes smart contracts and a multi-source data fusion, to the best advantage of the solutions that the blockchain and AI would offer in extensive operations.

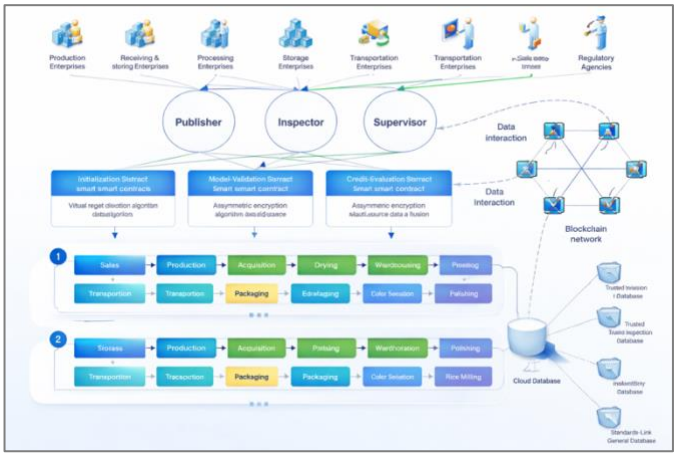

Figure 3. *Blockchain and AI-Driven Supply Chain Framework: This diagram illustrates the interaction between various enterprises (Production, Transportation, and Regulatory) through blockchain networks and smart contracts. It highlights the roles of the Publisher, Inspector, and Supervisor in ensuring secure data exchange and process automation, enhancing transparency and operational efficiency in material flow systems. The flow of operations, from sales to production, packaging, and warehousing, is supported by AI-driven decision-making and blockchain-based smart contracts for validation and credit evaluation (Charles et al., 2023; Wu et al., 2024).*

4. Discussion

The combination of blockchain and AI in supply chains and management has been a notable field of study in the past few years, due to their potential influence on transforming material flow systems. This study illustrates that the assembly of blockchain and its decentralized and immutable registry with AI and its predictive and automation ensures is changing supply chains and making them more transparent, secure, and

effective. Our study demonstrates that such integration can help to solve not only such critical concerns like data integrity, fraud prevention, and inefficiency of the conventional supply chains but also offers the possibility to optimize performance due to the ability to make better decisions and analyze data in real-time.

The main argument of the study is that blockchain and AI, together with each other, can provide significant advances in transparency and security of material flow in supply chains. According to multiple reports, blockchain technology can be used to establish immutable documentation of transactions, which is key in industries such as food, agriculture, and pharmaceuticals, where traceability and authenticity of products are paramount (Bhatia & Albarrak, 2023; Ellahi et al., 2023; Feng et al., 2020; Rejeb et al., 2020). The very nature of blockchain enables a real-time and immutable history of each transaction, so it is possible to trace each product on its way to the destination without any chances of falsifying records and committing fraud. These results correspond to the previous study by Wei et al. (2020), who emphasized the security benefits of blockchain due to decentralized consensus mechanism, which guarantees data integrity in networked systems (Wei et al., 2020).

Also, it is more transparent because of the use of smart contracts, which is one of the main features of blockchain technology, as it automatizes things and makes certain that the terms of agreements are automatically fulfilled as soon as a set of pre-defined conditions is satisfied (Mik, 2017; Rejeb et al., 2020). This automation will decrease the number of intermediaries and human factor involved which will reduce error and any possible manipulation of data. This transparency is also enhanced by the usage of AI that allows predictive analytics and timely decision-making, so that all participants in the producers, transport, and regulating industries can have instant access to the available information that is both accurate and valid (Felzmann et al., 2020).

The blockchain-based traceability provided in the dairy industry in India has been reported by Ellahi et al. (2023), where blockchain is used in order to guarantee safety and traceability, by storing all the supply chain activities (Ellahi et al., 2023). This is further enhanced by AI which allows real time analysis of demand trend/pattern, transportation efficiency, and stock levels that enables more informed decisions to be made. These developments, which as we have seen in the results help avert fraudulent activities, also lead to transparency of the whole chain of supply and help in bringing accountability in the whole process (Borandag, 2023).

The combination of AI and blockchain comes in handy to streamline the efficiency of the supply chain. Machine learning and data mining algorithms are examples of AI techniques that are essential to analyzing extensive IoT devices and sensors in supply chains (Riad et al., 2024; W. Wang et al., 2018). With the use of these advanced algorithms, businesses will be able to forecast demand changes, potential bottlenecks, and optimize their logistics and inventory control in real-time (Helo &Shamsuzzoha, 2020; Wan et al., 2018). The findings of the current research underline the idea that AI can analyze big amounts of data, which will positively impact the decision-making process and enable more efficient and responsive supply chains.

Moreover, AI along with blockchain increases operational efficiency as it automates various manual operations that usually take time and are stigmatized by human error. In the case exemplified in the figure, coordination of these technologies in the various stages of the supply chain, such as sales and production, warehousing and transportation simplifies material movement, as all the stages are monitored and controlled with precise information. This flawless data transmission enhances communication and coordination between many stakeholders as blockchain enables real-time information on the condition of goods, whereas AI provides predictive analytics of more accurate forecasting and planning (Rejeb et al., 2019).

In particular, the application of AI to managing and warehouse optimization and inventory, as seen by the example of Lu et al., (2022) can lead to substantial decreases in costs of operation and help avert overstocking or stockouts. It is possible to use AI algorithms to analyze the past, and make a prediction of the future demand with a high level of success, allowing warehouses to be stocked accordingly, which directly translates into cost reduction and increased customer satisfaction (Lu, 2019). This is in line with reports by Rejeb et al. (2019) who had postulated that optimization in AI will result in lower operational expenses and an increased utilization of resources, and that blockchain will allow such a process to be secure and transparent (Rejeb et al., 2019).

The adoption of blockchain and AI into supply chains is equally fraught with a variety of challenges, most notably with the idea of scalability, security, and interoperability. Scalability is a frequently cited location issue when it comes to large-scale organizations operating with blockchain, because the technology takes considerable computing resources to process transactions (Bhatia & Albarrak, 2023; Ehsan et al., 2022). This is especially noticeable in case of large amounts of data that is created by IoT devices within a large-scale supply chain. The promise of increased security is offset by the inefficiency of decentralized blockchain, in terms of processing power and speed. As observed in the findings, a number of studies have noted that scalability has been among the most critical issues when it comes to blockchain application in the supply chain management, particularly in industries whose transactions are large (Bhatia & Albarrak, 2023; Borandag, 2023).

In an attempt to solve these scalability issues, recent accomplishments have been on enhancing blockchain consensus algorithms, including Proof of Stake (PoS) and

sharding, intended to lower the power consumption and computational value needed to validate a blockchain (Wei et al., 2020). Nevertheless, even with these improvements, the potential of blockchain to scale in practice is under-studied, with much of its deployments being currently in its infantile phase.

Moreover, whereas blockchain has important security benefits, such as providing data integrity and preventing unauthorized changes, other technologies, such as IoT, RFID, and QR codes, can offer vulnerability in the sphere of data encryption and device security (Ehsan et al., 2022; Ellahi et al., 2023). The IoT devices are specifically vulnerable to hacking and data breaches, and hence the security of such interconnection devices is a priority in future studies. Strong encryption codes and multi-level protection should be considered to secure the whole ecosystem configuration when these devices are exploited in addition to blockchain to end-to-end supply chain visibility.

Moving forward, blockchain and AI integration in supply chain management has enormous potential in the future. An embrace of blockchain and AI technologies such as machine learning and deep learning is likely to unlock predictive analytics and autonomous decision-making processes, as well as the creation of autonomous supply chain networks (Ehsan et al., 2022; Helo &Shamsuzzoha, 2020; Wei et al., 2020). The resilience of supply chains to disruptions and malicious acts might be further increased by the ability to use AI and improve the security capabilities of blockchain, which include fraud detection and anomaly detection.

Nevertheless, there is nothing glamorous on the way to broad adoption. The study says that despite the proven value of blockchain and AI, companies will still have to self-overcome a number of obstacles, such as the cost of building, complexities of integration, and the issues of regulation (Bhatia & Albarrak, 2023; Ehsan et al., 2022). Additionally, how blockchain affects the environment, especially its energy-use in proof-of-work systems, will also become a crucial issue in the future. Future studies should aim to come up with energy-saving blockchain architectures and make sure that the adoption of such technologies is scalable and sustainable.

To advance the applicability of blockchain technology in supply chain logistics in the future, researchers must improve the scalability and energy efficiency of the technology, especially in large-scale operations. It is possible to explore hybrid blockchain system structures, like using a hybrid chain of the private and the public chains, which could be more efficient. Also, there is a necessity to enhance the safety of IoT and RFID systems that use blockchain and AI to overcome vulnerabilities. Under the umbrella area of AI-based automation, especially predictive analytics and autonomous decision-making will further streamline supply chain operations. Academia, industry and regulatory agencies cooperative efforts are important to come up with standard frameworks that would facilitate easy integration to solve both technological and regulatory issues.

5. Conclusion

The integration of blockchain and AI in supply chain management significantly enhances transparency, security, and efficiency in material flow systems. Blockchain provides secure, immutable records, while AI enables predictive analytics and real-time decision-making, optimizing operations. However, challenges such as scalability, security vulnerabilities, and system integration remain. Despite these hurdles, the potential benefits of combining these technologies are substantial, offering improved traceability, reduced fraud, and streamlined operations. Future advancements in blockchain scalability, AI-driven automation, and security protocols will further solidify the role of these technologies in transforming supply chains, making them more resilient and efficient in the long term.

Author Contributions

M.F.A.B. conceptualized the study, conducted data analysis, and drafted the manuscript.

K.R.H.S. contributed to methodology development, literature review, data interpretation, and manuscript revision. Both authors reviewed and approved the final manuscript.

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