



Blockchain and AI Synergies in Enhancing Supply Chain Transparency

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Abstract

The convergence of blockchain technology and artificial intelligence (AI) holds significant promise for enhancing transparency in supply chain management. Blockchain, with its decentralized, immutable ledger, ensures data integrity and traceability, while AI provides the analytical power needed to interpret and optimize supply chain data. This explores the synergies between these two technologies and their potential to transform supply chain operations by improving visibility, efficiency, and decision-making. Blockchain offers a secure, transparent, and real-time record of transactions and movements within the supply chain, allowing stakeholders to access trustworthy data without the need for intermediaries. By incorporating AI, the data stored on the blockchain can be analyzed for predictive insights, anomaly detection, and automated decision-making, enabling proactive management of supply chain risks. AI-powered analytics can process the vast volumes of data generated in supply chains, detecting patterns and trends that might otherwise remain unnoticed. This capability is further amplified by blockchain's immutable nature, which ensures that the data used by AI algorithms is both accurate and tamper-proof. The combination of blockchain and AI can also foster greater collaboration among supply chain partners by creating a shared platform for real-time data exchange, improving coordination and trust across the network. The integration of these technologies addresses common supply chain challenges, such as fraud, counterfeiting, and inefficiencies, and offers a pathway to a more transparent, resilient, and responsive supply chain ecosystem. This outlines the mechanisms through which blockchain and AI can work together to enhance supply chain transparency, examining key use cases, challenges, and the future potential of these technologies in modern supply chains.

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1. Introduction

The flow of products, services, and information amongst suppliers, manufacturers, distributors, and customers is a component of supply chains, which are intricate, multi-tiered networks (Ezeamii *et al.*, 2023; Obianyo *et al.*, 2024). Providing real-time, precise, and reliable information on the movement of goods and services to all stakeholders is one of the major issues facing contemporary supply chains. Inefficient supply chains, fraud, fake goods, and a lack of accountability can result from a lack of transparency, which makes it challenging for businesses to gain the trust of partners and customers (Folorunso *et al.*, 2024; Bello *et al.*, 2024). Additionally, a lack of visibility into supply chain activities can hamper effective decision-making, particularly in managing risks such as supply shortages, demand fluctuations, and disruptions due to geopolitical or environmental factors.

There has never been a greater need for increased visibility and responsibility as the global supply chain landscape becomes more data-driven and integrated. Paperwork, spreadsheets, and manual audits traditional means of tracking products and confirming transactions cannot provide the amount of transparency needed for contemporary supply chains (Ayo-Farai *et al.*,

2023; Ezeamii *et al.*, 2023). Artificial intelligence (AI) and blockchain are two emerging technologies that are being used more and more to improve supply chain transparency in order to address these issues.

The decentralized, distributed ledger system known as blockchain technology is renowned for its capacity to produce safe, transparent, and unchangeable transaction records. Information regarding a particular transaction is contained in each block of the chain, which are connected in such a way that it is nearly hard to change or tamper with the data (Ariyibi *et al.*, 2024; Adewuyi *et al.*, 2024). This ensures the integrity of the data being shared by giving all parties involved access to a trustworthy, transparent record. In supply chain management, where product authenticity, security, and traceability are critical, blockchain is very helpful.

AI, on the other hand, includes a wide range of technologies, such as machine learning, natural language processing, and predictive analytics, that are intended to mimic human intelligence. Large data sets can be swiftly processed and analyzed by AI, which yields actionable insights and helps supply chains run more efficiently. AI has applications in supply chain management, including demand forecasting, inventory management optimization, fraud detection, disruption prediction, and logistics efficiency improvement. Businesses may greatly increase operational efficiency and decision-making by utilizing AI's capacity to identify trends and generate data-driven forecasts.

Although blockchain and artificial intelligence alone have unique strengths, their combination provides a potent remedy for supply chain transparency issues. In order to trace products along the supply chain, blockchain can offer the safe, verifiable data required. This ensures that every transaction is clearly recorded and cannot be changed or fabricated (Adaramola *et al.*, 2024; West, Kraut & Ei Chew, 2019). But when blockchain is paired with AI, which can handle and analyze the vast volumes of data produced by blockchain networks, the true potential of blockchain is revealed. By spotting patterns, streamlining procedures, and anticipating possible problems before they materialize, AI can transform this data into useful insights.

Based on real-time data, AI can evaluate blockchain data to estimate demand, recommend ideal inventory levels, or spot possible supply chain delays. All parties involved can obtain precise information and make well-informed decisions thanks to the intelligent, transparent, and adaptable supply chain system that is produced by the combination of various technologies (Montecchi *et al.*, 2021; Oriekhoe *et al.*, 2024). Additionally, combining blockchain with AI improves security and accountability—two important factors in sectors like luxury goods, food safety, and pharmaceuticals where fraud and counterfeiting are prevalent issues. Businesses can guarantee transparency, boost productivity, cut expenses, and build a more robust supply chain that can better tolerate disruptions by fusing the predictive capabilities of AI with the traceability of blockchain (Talla, 2022; Rane *et al.*, 2023). The convergence of blockchain and AI technologies represents a transformative opportunity for supply chain management. By leveraging the strengths of both, organizations can address the pressing need for transparency, enhance trust among stakeholders, and improve overall supply chain performance. This integration offers a robust solution to the current challenges faced by global supply

chains, paving the way for more efficient, transparent, and secure systems in the future (Tyagi, *et al.*, 2024; Talla, 2022).

2. Methodology

The PRISMA methodology for exploring the synergies between Blockchain and AI in enhancing supply chain transparency involves a systematic process of selecting, reviewing, and analyzing relevant literature. This approach ensures a comprehensive and transparent evaluation of existing research on the integration of blockchain and AI technologies in supply chain management.

The first step in the methodology is the identification of relevant studies through a broad search of academic databases such as Google Scholar, Scopus, Web of Science, and others. Keywords related to "Blockchain", "Artificial Intelligence", "Supply Chain Transparency", "Synergies", and "Integration" are used to capture studies focused on the intersection of these technologies. The search strategy is designed to include a diverse set of sources, including peer-reviewed journal articles, conference papers, and industry reports, ensuring a broad view of the field.

Next, inclusion and exclusion criteria are applied to the studies. Studies are included if they specifically address the use of blockchain and/or AI in supply chain transparency, provide empirical evidence or case studies, and contribute to the theoretical understanding of how these technologies can enhance supply chain management. Excluded are articles that do not focus on both blockchain and AI, those that lack empirical data, and studies not relevant to the supply chain context. The selection process also considers studies that explore technical, operational, and managerial aspects of blockchain and AI integration.

After identifying the relevant studies, data extraction focuses on key themes such as the mechanisms through which blockchain and AI improve transparency, specific applications within supply chains, and the challenges and barriers to integration. The analysis also examines how these technologies work together to address issues such as fraud, inefficiency, data security, and operational visibility.

The synthesis of the results is then carried out by categorizing the findings into themes, such as transparency enhancement, decision-making, security improvements, and efficiency gains. Comparisons between different industries and sectors are made to understand how the synergies between blockchain and AI manifest in various supply chain contexts. Finally, the findings are presented in a structured format, providing insights into the current state of research, identifying gaps, and suggesting future research directions. This methodology allows for a holistic understanding of how blockchain and AI can collectively improve supply chain transparency, offering valuable insights for both academic research and practical applications in the supply chain industry.

2.1 Blockchain in Supply Chain Transparency

A decentralized and distributed ledger system called blockchain technology is becoming more widely acknowledged as a vital instrument for improving supply chain efficiency and transparency. Fundamentally, blockchain is a digital ledger that keeps track of transactions across numerous computers in a manner that guarantees the data is safe, transparent, and unchangeable (Hellani *et al.*, 2021; Zaabar *et al.*, 2021). As a result of these transactions

being classified into "blocks," they are connected in a chain, hence the term "blockchain." Because the system is decentralized, no one organization can control the entire ledger, which makes it impervious to fraud and manipulation. The capacity of blockchain technology to guarantee data integrity and traceability is one of its key characteristics that makes it very helpful in supply chain management. Information regarding products as they progress through a traditional supply chain is frequently dispersed and kept in different systems, which increases the risk of mistakes, fraud, and inefficiencies (Xue *et al.*, 2021; Wieland, 2021). Blockchain, however, offers a single, immutable source of truth that records every transaction in real-time. High security and data integrity are ensured by the blockchain's inability to change data after it has been added without the network's consent. This is especially important for supply chains, where reliable, accurate information is essential.

For sectors where provenance and authenticity are crucial, like food, pharmaceuticals, and luxury items, blockchain's capacity to ensure traceability is especially beneficial. Stakeholders can confirm a product's legitimacy, evaluate its condition, and guarantee regulatory compliance by employing blockchain technology to monitor a product's path from its point of origin to its ultimate destination (Baralla *et al.*, 2021; Tsolakis *et al.*, 2021). The blockchain's capacity to capture each stage of the supply chain from cultivation, harvesting, and processing to shipping and retail on an unchangeable and easily accessible ledger makes this feasible.

Additionally, blockchain can be very helpful in supply chain transaction verification, which is crucial for building confidence between parties that might not otherwise be acquainted. Blockchain can do away with the need for middlemen, which are frequently used in traditional supply chain transactions to make sure that the conditions of a deal are fulfilled (Ahmad, 2024). Smart contracts, a characteristic of blockchain technology, lower the risk of conflicts and fraud by automatically executing and enforcing a contract's terms when predetermined conditions are satisfied (Hamledari and Fischer, 2021; Wahab *et al.*, 2023). These self-executing, automated contracts streamline the process and minimize expenses by guaranteeing that parties are only paid when predetermined terms are met.

Blockchain's decentralized and unchangeable structure is essential for enhancing supply chain visibility and trust. One person has the ability to alter or fabricate data in a conventional centralized system. Blockchain, on the other hand, guarantees that everyone involved has access to the same data and that any modifications made to the ledger are immediately accessible to all. This transparency raises accountability, lowers the possibility of fraud and mistakes, and improves the system's overall dependability (Surjono, 2022; Ayogu, 2023). Any changes to the ledger must be approved by several parties due to the consensus mechanism used by blockchain, which makes it nearly impossible to update data covertly.

A decentralized, immutable ledger system has many advantages for supply chains. The greater degree of trust between participants is among the most important advantages. The same transparent data is accessible to manufacturers, suppliers, retailers, and customers, which lowers the possibility of miscommunications or conflicts. Additionally, the effectiveness of blockchain's automated procedures lowers transaction costs and times by doing away

with middlemen and streamlining compliance checks. Additionally, businesses can monitor every stage of the supply chain thanks to blockchain's visibility, which improves decision-making and enables them to react swiftly to any interruptions or inefficiencies (Gligor *et al.*, 2022; Sallam *et al.*, 2023).

In addition to these advantages, blockchain enhances accountability, allowing for more ethical and sustainable supply chains. This is particularly crucial given the growing demand from investors and customers for transparent supply chains and products obtained responsibly. Blockchain helps firms verify their commitment to sustainability by delivering verifiable documentation of responsible sourcing and production (Kshetri, 2022; Manfrino, 2024). Because blockchain technology ensures data integrity, improves traceability, and builds participant confidence, it has enormous potential to increase supply chain transparency. Blockchain's decentralized, unchangeable structure makes it safe and transparent to track goods, validate transactions, and automate procedures all of which increase productivity, lower fraud, and improve accountability. As blockchain continues to evolve and gain adoption, its applications in supply chain management are likely to expand, bringing further benefits to industries worldwide (Alzoubi, 2024; Francis Onotole, *et al.*, 2022).

2.2 AI in supply chain optimization

The creation of computer systems that are capable of carrying out operations that normally call for human intelligence, like pattern recognition, problem solving, and decision making, is known as artificial intelligence (AI) as shown in figure 1. AI has been used in a number of industries recently, including supply chain management, where it greatly improves operational accuracy, responsiveness, and efficiency. Businesses may improve the agility, resilience, and cost-effectiveness of their supply chains by utilizing AI technologies like robotics, machine learning, and natural language processing (Fatorachian, 2024; Sadeghi *et al.*, 2024).

AI is being utilized more and more in supply chain management to tackle important issues including logistics efficiency, inventory control, and demand forecasting. Demand forecasting is one of the main uses of AI in this field. Maintaining proper inventory levels, reducing stockouts, and avoiding excess inventory all depend on accurate demand forecasts. While AI-driven systems can evaluate enormous volumes of data, including real-time market movements, consumer behavior, weather patterns, and even sentiment on social media, traditional forecasting methods rely on historical data and expert judgment. Businesses can better synchronize production schedules, procurement strategies, and inventory levels by using machine learning algorithms that can recognize patterns and forecast future demand (Jampani *et al.*, 2023; Ramya *et al.*, 2024).



Fig 1: AI in Supply Chain Optimization

AI is essential to inventory management since it automates and improves stock control procedures. AI systems are able to forecast future stock needs, suggest reordering schedules, and track inventory levels in real-time. Taking into account variables like supplier lead times, sales velocity, and seasonal variations in demand, machine learning algorithms may also determine the ideal stock levels for a variety of products (Olanipekun Kehinde & Ayeni Naomi, 2024). Businesses may maintain a lean inventory while lowering the risks of stockouts and overstocking by using AI to help with just-in-time inventory management. AI-powered systems are able to respond more quickly to shifts in consumer demand and market conditions by dynamically adjusting inventory levels based on real-time data.

Logistics management is another crucial area where AI helps optimize the supply chain. AI-powered solutions streamline delivery schedules, fleet management, and route planning. Artificial intelligence (AI) algorithms can determine the most effective routes for delivery vehicles by examining data from GPS systems, traffic patterns, weather forecasts, and delivery histories. This lowers fuel consumption, transit time, and total logistics costs (Veluru, 2023; Olugbade *et al.*, 2022). Furthermore, by dynamically modifying routes in response to current conditions, AI can assist companies in enhancing last-mile delivery, guaranteeing timely and economical deliveries. In order to satisfy customer expectations for quicker, more dependable deliveries, these AI-driven optimizations are essential (Folorunso, *et al.*, 2024, Kolade, *et al.*, 2024).

AI is also quite useful for spotting supply chain irregularities and inefficiencies. Supply chains are intricate networks with many participants, procedures, and data exchanges. Artificial intelligence (AI) systems are able to keep an eye on these procedures and identify irregularities, like shipment delays, disparities in inventory information, or departures from production plans. Businesses can solve problems before they become more serious by using AI to analyze historical data and find patterns that point to inefficiencies (Zong and Guan, 2024; Aldoseri *et al.*, 2024). By identifying these inefficiencies early on, companies may take swift corrective action, which enhances supply chain performance overall. Furthermore, AI is essential for improving supply chain

predictive analytics. Predictive analytics forecasts future patterns and outcomes by utilizing machine learning models and past data. AI-driven predictive analytics can improve decision-making in supply chains in a number of areas, such as supplier management, demand planning, and inventory replenishment. Businesses may minimize interruptions and maximize resource allocation with this proactive approach. Businesses can take preventative action to lessen risks by using predictive analytics to help anticipate possible hazards like delays or shortages in supplies (Folorunso, *et al.*, 2024, Kolade, *et al.*, 2024).

Supply chains are changing as a result of artificial intelligence's capacity to evaluate enormous datasets and produce insights instantly. Businesses can transition from reactive decision-making to proactive, data-driven strategies by utilizing AI for optimization. Based on performance data, AI-driven systems can also recommend different logistics partners or suppliers, giving businesses the ability to make better decisions (Mittal & Bansal, 2024; Sanusi, 2023).

AI can also decrease lead times and increase product availability, which will increase customer satisfaction. AI helps companies keep a competitive edge in a market that is changing quickly by guaranteeing that goods are available when customers need them and that deliveries are made on schedule (Modgil *et al.*, 2022; Josimovski *et al.*, 2023). Traditional supply chain operations could be drastically changed by the use of AI in supply chain optimization. AI helps companies become more responsive and efficient by enhancing demand forecasting, inventory control, logistics optimization, and anomaly identification. AI-powered predictive analytics improves decision-making by offering practical insights that direct preemptive measures to reduce risks and maximize resource utilization. As AI continues to evolve, its role in supply chain optimization will only expand, creating new opportunities for businesses to streamline operations, reduce costs, and improve customer satisfaction (Belot, 2020; Olanipekun, Ilori & Ibitoye, 2020).

2.3 Synergies between blockchain and AI

Two revolutionary technologies that are changing industries worldwide are blockchain and artificial intelligence (AI). Although each technology has unique characteristics, supply chain operations could be improved by integrating them to improve decision-making, transparency, and data integrity. While AI uses algorithms to assess and forecast results based on data, blockchain uses its decentralized and unchangeable ledger to guarantee the security and reliability of data (Shinde *et al.*, 2023; Aakula *et al.*, 2024). Organizations can increase process efficiency, accuracy, and transparency particularly in supply chain management by integrating these technologies. Ensuring the integrity of data utilized by AI algorithms is one of the main ways that blockchain and AI work in tandem. Data is essential to AI systems' decision-making, pattern-spotting, and process optimization. However, the precision and dependability of the data entering the system determine how well AI-driven judgments turn out. Blockchain provides a transparent and safe method of recording data exchanges, which solves this problem. Because blockchain is decentralized, it is impervious to fraud, tampering, and unauthorized alterations, guaranteeing the accuracy and reliability of the data utilized by AI models (Tyagi *et al.*, 2024; Kuznetsov *et al.*, 2024). In supply chains, where data is often distributed across multiple stakeholders, blockchain provides a unified record that guarantees the authenticity of

data, ensuring that AI algorithms are working with reliable inputs. This reduces the risk of errors and biases in decision-making that can arise from flawed or manipulated data (Ajayi, Olanipekun & Adedokun, 2024).

Another important area where these technologies complement one another is in the complimentary functions of AI's analytical skills and blockchain's transparency. The main benefit of blockchain technology is its capacity to provide real-time transparency. The blockchain gives stakeholders a transparent, auditable record of all supply chain operations since every transaction is publicly accessible and unchangeable (Panda and Satapathy, 2021; Ronaghi, 2021). This degree of openness is essential for fostering mutual trust and guaranteeing legal compliance. However, AI can handle enormous volumes of data and derive valuable insights thanks to its analytical powers. When combined, blockchain's transparent data provides a reliable foundation for AI systems to analyze and make more accurate predictions or decisions. This synergy not only enhances operational efficiency but also strengthens accountability and trust within the supply chain (Ogunyankinnu, *et al.*, 2022, Kolade, *et al.*, 2022).

Combining real-time data from blockchain with predictive analytics from AI creates yet another important synergy between the two technologies. Blockchain is a great source of current information for AI systems because it provides the benefit of real-time tracking and updates. AI-driven prediction models can use this real-time data to predict future trends or occurrences, such changes in demand, possible supply chain interruptions, or inventory shortages (Muthukalyani, 2023; Narashimman *et al.*, 2024). AI can make better predictions and suggest practical actions to reduce risks or take advantage of opportunities if it has access to precise, real-time data. Because of this combination, businesses are able to make better decisions and take proactive rather than reactive action, which is crucial in the fast-paced and dynamic market settings of today.

Several supply chain scenarios show how blockchain and artificial intelligence (AI) may collaborate to build more secure and effective operations. The identification of fraud is one area where this synergy is especially beneficial. Supply chains are frequently vulnerable to fraud, including invoicing fraud, product counterfeiting, and misrepresentation of items (DuHadway *et al.*, 2022; Wang *et al.*, 2023). Every stage of a product's journey may be safely documented using blockchain, producing an unchangeable audit trail. After then, AI systems can examine this data to find any anomalies or trends that can point to fraud.

Tracking and improving travel routes for commodities is another use. Every movement of commodities, including their current position, handling circumstances, and delivery status, can be transparently and irrevocably recorded using blockchain technology (Elmay *et al.*, 2022; Ugochukwu *et al.*, 2022). This real-time data can then be used by AI to improve routes, lowering fuel usage, cutting down on delays, and increasing overall efficiency. Supply chains may become more responsive, agile, and economical by combining the predictive capabilities of AI with the transparency of blockchain technology (Kumar & Choudhury, 2024; Olanipekun, 2020).

Additionally, inventory management can be enhanced by combining blockchain technology with artificial intelligence. Blockchain data may be analyzed by AI to manage replenishment cycles, improve stock levels, and forecast

future demand. While AI models predict future demands based on historical data, seasonal trends, and real-time transactions, blockchain guarantees that inventory data is accurate and current (Ogunyankinnu, *et al.*, 2022, Kolade, *et al.*, 2022). Businesses can improve overall supply chain performance by minimizing excess inventory, reducing stockouts, and maintaining optimal inventory levels. Supply chain management might be completely transformed by combining blockchain technology with artificial intelligence (AI) to solve important issues including data integrity, transparency, decision-making, and operational efficiency. Blockchain offers a transparent and safe basis for real-time data, which is essential for AI systems to evaluate and produce precise forecasts. These technologies can improve inventory management, fraud detection, and route optimization through their synergies, which will ultimately result in supply chains that are more responsive, transparent, and efficient (Khan and Jalal, 2023; Vaka, 2024). Both technologies' combined influence on supply chain optimization is expected to grow as they develop further, providing even more chances for advancement and creativity.

2.4 Use cases and practical applications

Blockchain offers a transparent and safe basis for real-time data, which is essential for AI systems to evaluate and produce precise forecasts. These technologies can improve inventory management, fraud detection, and route optimization through their synergies, which will ultimately result in supply chains that are more responsive, transparent, and efficient (Khan and Jalal, 2023; Vaka, 2024). Both technologies' combined influence on supply chain optimization is expected to grow as they develop further, providing even more chances for advancement and creativity. One notable case study in the food industry is the collaboration between Walmart and IBM's Food Trust blockchain platform. Walmart uses blockchain to ensure food safety and enhance traceability across its supply chain. By integrating AI into this framework, the company can predict potential disruptions, optimize inventory management, and ensure the freshness of food products. Blockchain's immutable ledger securely records each step a product takes from farm to store, while AI algorithms analyze the data to identify patterns, such as optimal storage conditions or sales trends, to reduce waste and improve inventory decisions (Ilori & Olanipekun, 2020). This synergy between blockchain and AI ensures greater transparency for consumers, as they can trace the origin and journey of food products, promoting trust in the brand and enhancing overall food safety. Through these combined technologies, Walmart has been able to reduce the time needed to trace food products from days to mere seconds, effectively preventing safety issues like contamination outbreaks (Stecula *et al.*, 2024; Nair *et al.*, 2024).

Similarly, the pharmaceutical industry has also benefited from the integration of blockchain and AI to combat counterfeit drugs. Counterfeit pharmaceuticals are a significant global challenge that compromises patient safety and disrupts supply chains. Major pharmaceutical companies, such as Pfizer and GSK, have implemented blockchain-based solutions to track the authenticity of their products, ensuring that each item can be traced back to its source. AI is applied to analyze patterns in transaction data, flagging potential anomalies or fraud in real-time (Ajibola & Olanipekun, 2019, Olanipekun & Ayotola, 2019). For instance, when AI detects

irregularities in the movement of goods or discrepancies between recorded shipments and actual delivery times, the system can trigger an alert, preventing counterfeit products from entering the market. Blockchain provides an immutable, transparent record of every transaction, while AI automates the monitoring and verification process, improving the speed and accuracy of fraud detection (Adewale *et al.*, 2022; Bothra *et al.*, 2023).

In the luxury goods industry, blockchain and AI are being used to authenticate products and ensure their provenance. With the rise of counterfeit luxury items, high-end brands like LVMH and Prada have turned to blockchain to verify the authenticity of their products. By recording the entire lifecycle of a luxury item on a blockchain from the raw materials to the point-of-sale companies can ensure that their products are genuine and that their customers are purchasing items with guaranteed authenticity (Nermain *et al.*, 2022; Zimmermann *et al.*, 2023). AI enhances this system by analyzing sales and transaction data to detect counterfeit patterns or fraud in real-time, alerting stakeholders if any irregularities are identified. The combination of blockchain's secure, traceable records and AI's pattern recognition capabilities enables greater protection for brands, as well as trust among consumers (Kolade, *et al.*, 2021).

One of the most powerful applications of blockchain and AI in supply chain management is their role in real-time tracking of goods. Blockchain's decentralized, immutable ledger ensures that all stakeholders in a supply chain have access to the same, tamper-proof data. This transparency significantly improves the efficiency and accuracy of tracking goods in transit, as it removes the possibility of fraud, errors, or discrepancies in the system. When combined with AI, blockchain can be used to predict delivery times, optimize routes, and even monitor the condition of goods during transport (Olanipekun, Ilori & Ibitoye, 2020). If a shipment is delayed due to weather or geopolitical events, AI systems can automatically suggest alternative routes to avoid disruption, thereby improving efficiency and reducing costs. Another practical application is automated supply chain management. In industries such as automotive and electronics, manufacturers and suppliers use blockchain to record the movement of parts and components, while AI algorithms forecast demand, track inventory levels, and optimize the timing of orders. By automating these processes, businesses can minimize human errors, reduce lead times, and lower operational costs. AI can be trained to recognize patterns in data, such as seasonal demand spikes or supplier lead times, and make recommendations to adjust supply chain operations accordingly. Blockchain guarantees the integrity of this data, ensuring that all stakeholders can trust the information being used for decision-making. This combination of real-time tracking, predictive analytics, and automated workflows makes supply chains more agile, resilient, and responsive to market fluctuations (Paramesha *et al.*, 2024; Hossain *et al.*, 2024).

The integration of blockchain and AI also plays a key role in enhancing traceability and accountability in supply chains. The transparency provided by blockchain's distributed ledger ensures that every transaction is recorded, allowing stakeholders to trace goods at any point in the supply chain. AI algorithms can analyze this data to detect discrepancies, delays, or potential risks that could compromise the integrity of the supply chain. In addition, blockchain's immutability reduces the potential for fraud by making it difficult for bad

actors to alter or falsify transaction records. AI helps identify any deviations from the expected transaction patterns, flagging any unusual activity for investigation.

Finally, the reduction of fraud is one of the most compelling benefits of combining blockchain and AI in supply chain management. Blockchain ensures that every step of a product's journey is recorded, making it easier to spot fraudulent activities, such as the diversion of goods or counterfeiting. AI further supports this by analyzing patterns and identifying irregularities in real-time, enabling companies to respond quickly to fraudulent attempts. Whether it's counterfeit luxury goods or fake pharmaceuticals, the synergy between blockchain's secure data recording and AI's analytical capabilities makes it significantly more difficult for fraud to occur unnoticed (Yiu, 2021; Trautmann *et al.*, 2024). The integration of blockchain and AI offers significant advantages in enhancing supply chain transparency. By ensuring data integrity, improving real-time tracking, automating supply chain management, and reducing fraud, these technologies work together to address long-standing challenges in various industries. From food safety to pharmaceuticals and luxury goods, the synergy between blockchain and AI provides a powerful solution for improving efficiency, traceability, and accountability, leading to more resilient and trustworthy supply chains.

2.5 Challenges and barriers to implementation

Blockchain technology and artificial intelligence (AI) have the potential to revolutionize supply chain transparency, but there are substantial obstacles to overcome before this can happen (Charles *et al.*, 2023; Oriekhoe *et al.*, 2024). To fully realize the potential of these technologies, these obstacles which cut across organizational, operational, and technical domains must be removed. Technical integration challenges, data security and privacy issues, scalability constraints, and organizational resistance to change are some of the main problems as shown in figure 2.

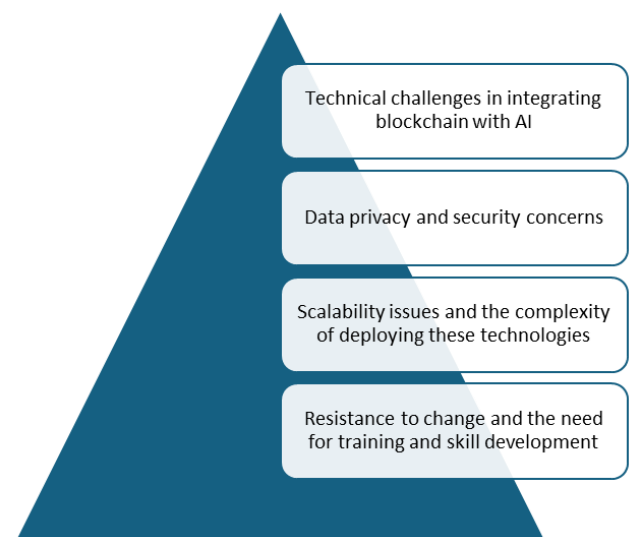


Fig 2: Challenges and Barriers to Implementation

The technological difficulty of combining blockchain technology with AI systems is one of the main obstacles. AI and blockchain have different operational requirements and designs. While AI systems need access to vast, dynamic datasets for model training and decision-making, blockchain uses a decentralized approach with consensus processes that

favor data immutability and transparency. It is necessary to close gaps in latency control, computing resource allocation, and data format compatibility in order to synchronize these two technologies. Furthermore, the pace at which AI algorithms, particularly those that depend on real-time data processing, can function may be constrained by blockchain's intrinsic design for sequential data recording. This discrepancy may lead to ineffective system operation and impede prompt supply chain decision-making. Additionally, integrating blockchain's cryptographic and consensus features with AI-driven analytics platforms demands sophisticated interoperability protocols, which are still underdeveloped and evolving (Zuo, 2024; Rahman *et al.*, 2024).

Data security and privacy provide yet another significant challenge. Blockchain raises worries about the vulnerability of sensitive supply chain data, including trade secrets, personal information, and private corporate information, even while it guarantees openness through its distributed ledger. Data that has been stored on a blockchain is unchangeable and accessible to all network users, which may be in violation of privacy laws like the General Data Protection Regulation (GDPR) in the EU. The need for large datasets to train machine learning models in AI applications may also put private data at danger of unintentional disclosure. It is a difficult and continuous task to guarantee that blockchain and AI systems abide by current data protection regulations while preserving operational effectiveness. Methods such as zero-knowledge proofs, differential privacy, and permissioned blockchain networks are being explored to mitigate these concerns but require further research and standardization.

Adoption of these technologies is further complicated by scalability concerns, especially in global supply networks. Blockchain networks frequently experience excessive latency and limited transaction throughput as a result of consensus techniques like Proof of Work or Proof of Stake. When supply chains include millions of transactions every day involving several players and geographical locations, this bottleneck presents a serious problem. According to Li *et al.* (2023) and Duan *et al.* (2024), AI systems necessitate a strong infrastructure for data processing, storage, and model training resources, which may not be consistently accessible throughout global supply chain networks, particularly in poor nations. For reliable and scalable performance, the combination of blockchain and AI necessitates large

expenditures in cloud services, edge computing, and IT infrastructure. Moreover, harmonizing these technologies across diverse regulatory environments and varying levels of digital maturity among supply chain partners adds another layer of complexity.

Other non-technical obstacles include reluctance to change and organizational inertia. Because of the perceived risks, expenses, and uncertainties involved with digital transformation, many businesses are reluctant to implement new technology. Decision-makers and staff may not be well-versed in blockchain and AI technologies, which could raise doubts about their viability and usefulness. The requirement for thorough training and skill development exacerbates this opposition. There is now a shortage of skilled workers with knowledge of supply chain analytics, software development, data science, and cryptography needed to implement blockchain and AI solutions. Organizations run the danger of deploying underutilized or misaligned technical solutions that don't produce the desired results if they don't make focused investments in workforce upskilling and cross-functional collaboration (Whig *et al.*, 2024; Marlapudi and Lenka, 2024). Although blockchain and artificial intelligence (AI) have the potential to revolutionize supply chain transparency, organizational resistance, scalability issues, data protection issues, and technological integration challenges make their adoption difficult. A diversified approach is needed to address these problems, one that incorporates workforce development, regulatory compliance, infrastructure investment, and cross-industry cooperation. Businesses can only fully benefit from the synergistic advantages of blockchain and AI in creating more resilient, transparent, and efficient global supply chains by removing these obstacles.

2.6 Future directions and potential

Supply chain management is about to undergo a radical change as a result of the combination of blockchain technology with artificial intelligence (AI) (Eyeghre *et al.*, 2023). As these technologies develop further, their integration will present previously unheard-of chances to improve global supply networks' resilience, efficiency, and transparency as shown in figure 3. It is anticipated that future advancements will encourage sustainability and moral behavior, enable new business models, and spark creativity. To fully realize these revolutionary potentials, deliberate stakeholder involvement and strategic planning are crucial.

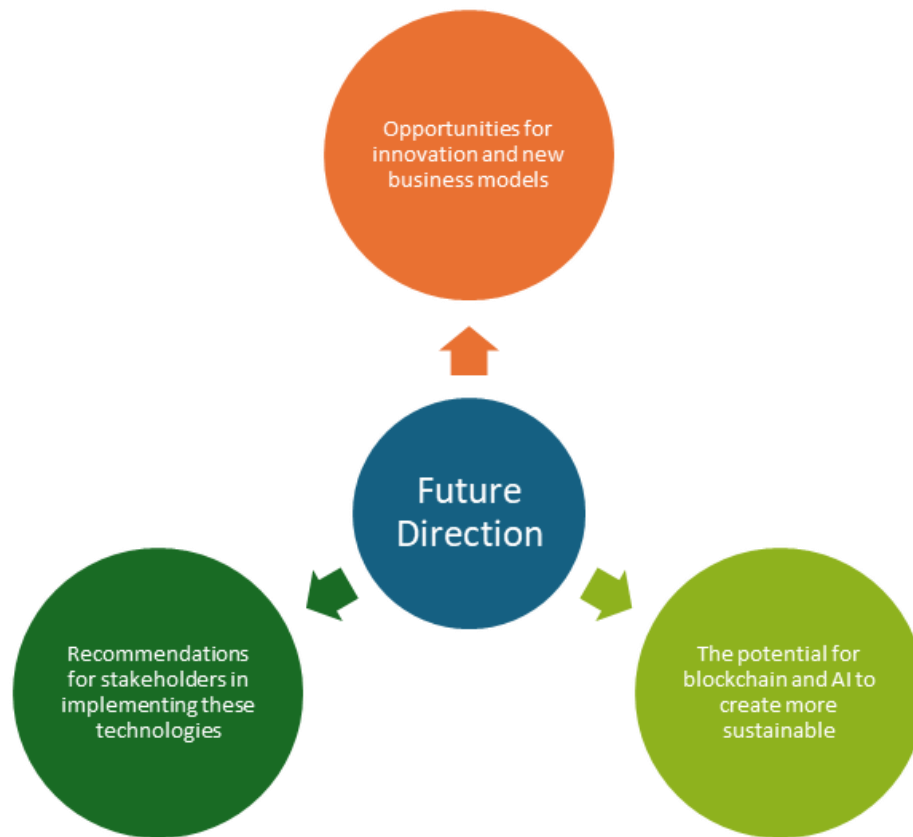


Fig 3: Future Directions and Potential

In the future, supply chain technology will see tremendous advancements in blockchain and artificial intelligence. One of the main technological limitations of the present blockchain platforms will be addressed by emerging blockchain innovations including sharding, layer-two solutions, and interoperability protocols, which will improve scalability and transaction speed. At the same time, explainable AI (XAI), reinforcement learning, and federated learning will be developed, allowing for more precise, safe, and decentralized supply chain decision-making (Ajibola *et al.*, 2024; Ezeamii *et al.*, 2024). These developments will facilitate large-scale predictive maintenance, anomaly detection, and real-time analytics. When used in tandem, blockchain will provide the trustworthy data infrastructure, while AI will offer intelligent analytics to derive actionable insights, resulting in a more autonomous and adaptive supply chain ecosystem.

There are a lot of chances for innovation and new business models because of this evolution. By automating agreements that are triggered by verifiable blockchain data, smart contracts can reduce administrative overhead and enable dynamic pricing models while streamlining payment processing, inventory management, and procurement. In the meantime, traditional supply chain insurance and compliance procedures can be revolutionized by AI-powered risk modeling and blockchain-based audit trails, producing value-added services that were previously impractical because of data fragmentation and stakeholder mistrust (Adhikari *et al.*, 2024).

Blockchain and AI have the potential to promote more ethical and sustainable supply chains in addition to increasing operational efficiency. Businesses need to demonstrate that their products are both environmentally benign and ethically manufactured in light of growing consumer and regulatory

pressure for responsible sourcing and environmental accountability. Stakeholders can track the environmental and social impact of products thanks to blockchain's immutable records at every stage of the supply chain, from the procurement of raw materials to the final delivery. According to Eyeghre *et al.* (2024) and Ramdoo, *et al.*, (2021), artificial intelligence (AI) can evaluate sustainability performance, identify supply chain hazards (such as child labor or deforestation), and maximize resource use. Similar to electronics and fashion, these technologies aid in confirming the legitimacy of products and guaranteeing the observance of moral labor standards. These apps encourage brand trust and customer loyalty in addition to compliance.

Suggestions for stakeholders are essential if blockchain and AI are to be fully utilized. In order to foster innovation and resolve legal issues pertaining to data ownership, privacy, and liability in AI-blockchain systems, governments and regulators should first establish supportive policy frameworks. Second, in order to develop the internal competencies required for technology adoption, firms need to invest in talent development and digital infrastructure. Learning and innovation can be accelerated by partnerships with industry consortia, research institutions, and technology providers (ADEOYE *et al.*, 2024; Arshad, 2023). Third, for supply chain partners to seamlessly integrate blockchain and AI, standardization of data formats, APIs, and interoperability protocols is crucial. Finally, ethical standards should be set to guarantee that blockchain systems adhere to privacy and equity principles and that AI algorithms are open, equitable, and responsible. Blockchain and artificial intelligence have a bright and revolutionary future in supply chain transparency. These technologies have the potential to completely transform supply chains, enabling more robust, sustainable, and ethical global trade systems in addition to

smarter corporate operations (Ogunyankinnu *et al.*, 2022; Folorunso *et al.*, 2024). Stakeholders from a variety of industries may realize this potential and usher in a new era of intelligent, transparent, and reliable supply chains by taking purposeful strategic action.

3. Conclusion

Blockchain technology and artificial intelligence (AI) have the potential to revolutionize supply chain transparency and operational effectiveness. While AI offers strong capabilities for analyzing massive datasets, predicting demand, streamlining logistics, and spotting irregularities, blockchain's immutable, decentralized ledger guarantees the integrity and traceability of data along the supply chain. These technologies work in concert to have a synergistic effect, with blockchain using AI's analytical skills to identify anomalies and enhance operational supervision and AI using reliable data from blockchain to make precise predictions and judgments.

There are a number of obstacles to the broad adoption of blockchain and AI in supply chains, notwithstanding their combined potential. These include issues with data security and privacy, scalability constraints, technical difficulties with system compatibility, and a general reluctance to change. Addressing these obstacles will need ongoing multidisciplinary research and cooperation across stakeholders, including governments, businesses, academic institutions, and technology developers. Working together may spur the creation of standardized frameworks, encourage information exchange, and develop instructional programs to equip workers with the skills they need for successful implementation.

These technologies will have a significant long-term impact on global supply chains. Blockchain and artificial intelligence (AI) can increase supply chain resilience, encourage ethical sourcing, and lower fraud and counterfeiting by offering real-time visibility, enhanced trust, and intelligent automation. Additionally, they can encourage the development of novel, inclusive, and flexible business models. In the end, combining blockchain technology with artificial intelligence is not just a technological breakthrough but also a strategic necessity that will influence the development of open, sustainable, and effective global supply chain ecosystems in the future.

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