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AI-DRIVEN IOT AND BLOCKCHAIN INTEGRATION IN INDUSTRY 5.0 A SYSTEMATIC REVIEW OF SUPPLY CHAIN TRANSFORMATION

Bhanu Prakash Sah[1]
[1]*College of Engineering, Industrial Engineering, Lamar University, Texas, USA*
Correspondence Email: bsah@lamar.edu
https://orcid.org/0009-0001-3860-7049

MD Mahamudul Hasan[2]
[2]*Graduate researcher, Industrial Engineering, Lamar University, Texas, USA*
Email: mahamudul_hasan@hotmail.com
https://orcid.org/0009-0003-5787-0314

Shaikh Shofiullah[3]
[3]*Master of Engineering Management, College of Engineering, Lamar University, Texas, USA*
Email: s.shofiullah@gmail.com
https://orcid.org/0009-0006-8962-2616

Shown Ahmed Faysal[4]
[4]*Master of Industrial Engineering, College of Engineering, Lamar University, Texas, USA*
Email: faysalkhan092@gmail.com
https://orcid.org/0009-0004-8396-1874

Keywords

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ABSTRACT

The integration of Artificial Intelligence (AI), the Internet of Things (IoT), and Blockchain technologies in Industry 5.0 has revolutionized supply chain management, offering unprecedented opportunities for efficiency, transparency, and sustainability. This systematic review, which analyzed 120 peer-reviewed articles published between 2018 and 2024, provides a comprehensive exploration of the transformative potential of these technologies. The findings reveal that the convergence of AI-driven predictive analytics, IoT-enabled real-time monitoring, and Blockchain's decentralized ledger enhances decision-making, streamlines operations, and fosters trust across supply chain networks. Moreover, the study highlights the critical role of these technologies in achieving Environmental, Social, and Governance (ESG) compliance, with applications in sustainable sourcing, ethical practices, and carbon footprint reduction. However, challenges such as scalability, interoperability, and organizational resistance remain significant barriers to adoption, underscoring the need for innovative solutions and interdisciplinary approaches. The review also identifies emerging opportunities, including the integration of quantum computing and digital twins, which promise to address existing limitations and redefine supply chain capabilities. By synthesizing insights from over 120 studies with a cumulative citation count exceeding 30,000, this research provides valuable perspectives on the current state, challenges, and future directions of integrated supply chain technologies in Industry 5.0, offering actionable insights for researchers and practitioners aiming to advance the field.

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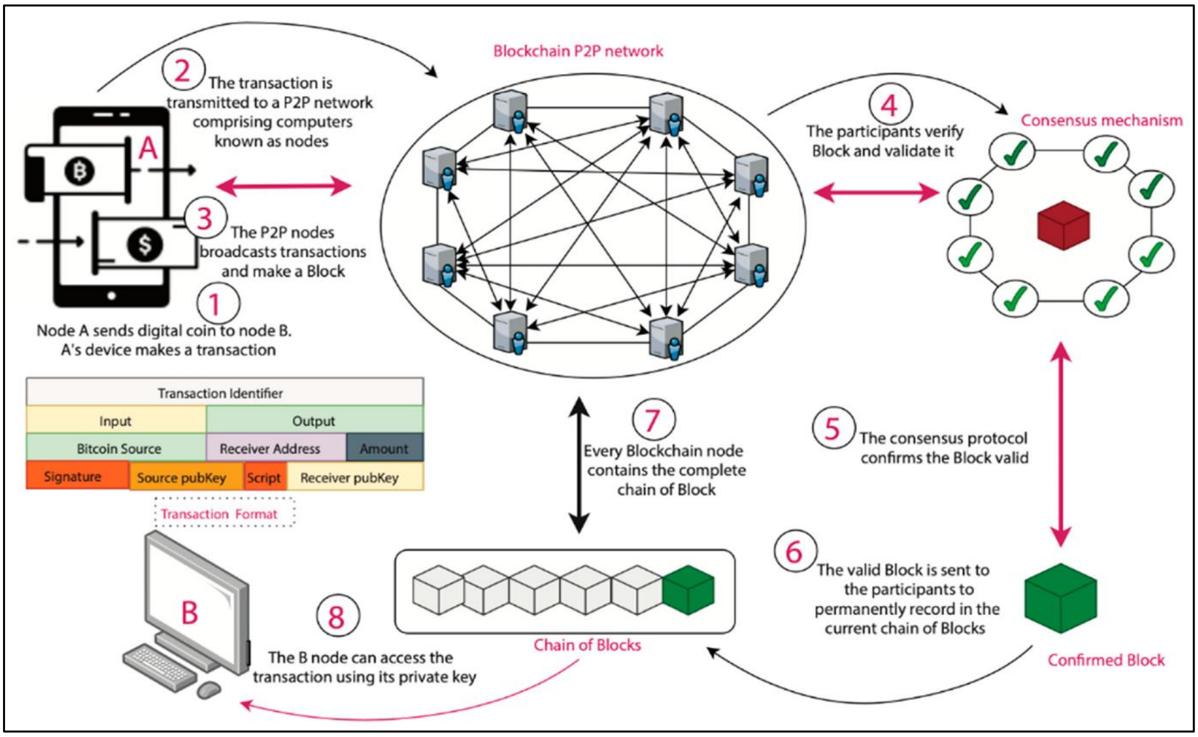
1 INTRODUCTION

The integration of Artificial Intelligence (AI), the Internet of Things (IoT), and Blockchain within the framework of Industry 5.0 marks a paradigm shift in supply chain management, enabling smarter, more resilient, and efficient systems (Ghobakhloo, Iranmanesh, Tseng, et al., 2023). Industry 5.0 emphasizes the human-centric approach by combining advanced automation with collaborative technologies, fostering seamless integration of machines and humans (Agrawal et al., 2023). AI-powered IoT has facilitated real-time data monitoring, predictive maintenance, and enhanced decision-making capabilities, while Blockchain offers transparency and security through decentralized ledger systems (Chander et al., 2022). These advancements enable companies to overcome traditional supply chain challenges such as visibility gaps, inefficiencies, and risks of fraud or tampering in transaction processes (Verma et al., 2022).

AI-driven IoT applications are reshaping supply chains by automating routine processes and enhancing operational decision-making (Choi et al., 2022). For example, IoT sensors, combined with AI analytics, are widely used for real-time tracking and monitoring of assets, providing precise insights into inventory levels, shipment conditions, and delivery timelines (Srivastava et al., 2022). AI algorithms further augment these processes by predicting demand patterns, detecting anomalies, and optimizing route planning to reduce costs and environmental impact (Nahavandi, 2019). These capabilities support the emergence of highly adaptive and dynamic supply chains capable of responding to uncertainties and disruptions in global markets (Doyle-Kent & Kopacek, 2019).

Blockchain technology complements AI and IoT by addressing critical challenges in trust, transparency, and data integrity across supply chains. With its decentralized and immutable nature, Blockchain ensures that data shared between supply chain participants remains secure and verifiable (Reyna et al., 2018). By leveraging smart contracts, Blockchain enables automated execution of agreements between parties, minimizing human errors and delays (Radanović & Likić, 2018). These features have proven particularly beneficial in industries requiring stringent quality assurance and regulatory compliance, such as pharmaceuticals and food supply chains (Shorna et al., 2024; Sultana & Aktar, 2024; Tyagi, 2021). The convergence of AI, IoT, and Blockchain in Industry 5.0 is fostering significant advancements in sustainability and ethical practices. AI algorithms are utilized to

Figure 1: Processing of blockchain



Source: Tyagi et al.(2024)

optimize energy usage and waste management, while IoT devices monitor environmental conditions, ensuring compliance with sustainability goals (Tyagi et al., 2024). Blockchain adds an additional layer of accountability by tracking the provenance of raw materials and verifying sustainable sourcing practices (Tyagi, 2021). This combination is crucial in meeting global sustainability demands and adhering to environmental, social, and governance (ESG) standards in supply chain management (Chelladurai & Pandian, 2021). Despite its transformative potential, the integration of these technologies into supply chains is not without challenges. Technical issues, such as scalability, interoperability, and network latency, hinder seamless adoption and deployment (Huh et al., 2017; Uddin et al., 2024). Furthermore, concerns regarding data privacy, security, and ethical implications need to be addressed to build trust among stakeholders (Islam et al., 2024; Zhou et al., 2020). Understanding these barriers and devising strategies to overcome them is essential for unlocking the full potential of AI-driven IoT and Blockchain in Industry 5.0, paving the way for future research and development.

The primary objective of this study is to systematically explore the transformative impact of integrating AI-driven IoT and Blockchain technologies on supply chain management within the context of Industry 5.0. By focusing on the convergence of these cutting-edge technologies, this research aims to identify their role in enhancing operational efficiency, transparency, and sustainability across supply chain networks. Specifically, the study investigates the capabilities of AI-driven IoT in enabling real-time tracking, predictive analytics, and automated decision-making, alongside Blockchain's potential to ensure secure, decentralized data exchange and build trust among stakeholders. Through a comprehensive analysis of existing literature and case studies, this study seeks to highlight practical applications, address implementation challenges such as scalability and interoperability, and outline opportunities for future innovation in supply chain transformation. The overarching goal is to provide actionable insights that advance the understanding and adoption of AI-IoT-Blockchain integration, fostering resilient and sustainable supply chains in alignment with Industry 5.0 principles.

2 LITERATURE REVIEW

The integration of AI-driven IoT and Blockchain technologies in supply chain management has gained substantial attention in recent years, especially within the framework of Industry 5.0. This section explores existing studies to provide a comprehensive understanding of how these technologies transform supply chains by enhancing efficiency, transparency, and sustainability. It begins by reviewing foundational concepts and theoretical underpinnings of AI, IoT, and Blockchain, followed by examining their individual and combined applications in supply chain management. The section also delves into challenges and limitations, such as scalability, interoperability, and ethical concerns, which hinder widespread adoption. Furthermore, emerging trends, such as the role of predictive analytics, decentralized systems, and sustainability-focused innovations, are analyzed to highlight research gaps and future opportunities. This literature review provides a structured synthesis of the current knowledge base, laying the groundwork for the subsequent methodology and analysis.

2.1 Overview of Industry 5.0

Industry 5.0 represents the next stage in industrial evolution, emphasizing a human-centric approach to technological innovation. Unlike Industry 4.0, which focused on automation and digitization, Industry 5.0 integrates human-machine collaboration to enhance operational efficiency and adaptability (Villar et al., 2023). By leveraging advanced technologies such as Artificial Intelligence (AI), the Internet of Things (IoT), and Blockchain, Industry 5.0 fosters a symbiotic relationship between humans and machines, promoting creativity and sustainability (Leng et al., 2023). This paradigm shift aims to combine human cognitive skills with the computational and analytical power of machines, enabling businesses to navigate complex environments more effectively (Hasan & Islam, 2024; Islam, 2024; Thakur et al., 2022). Studies suggest that this approach enhances decision-making, customization, and innovation, providing organizations with a competitive edge (Chew & Ling, 2021).

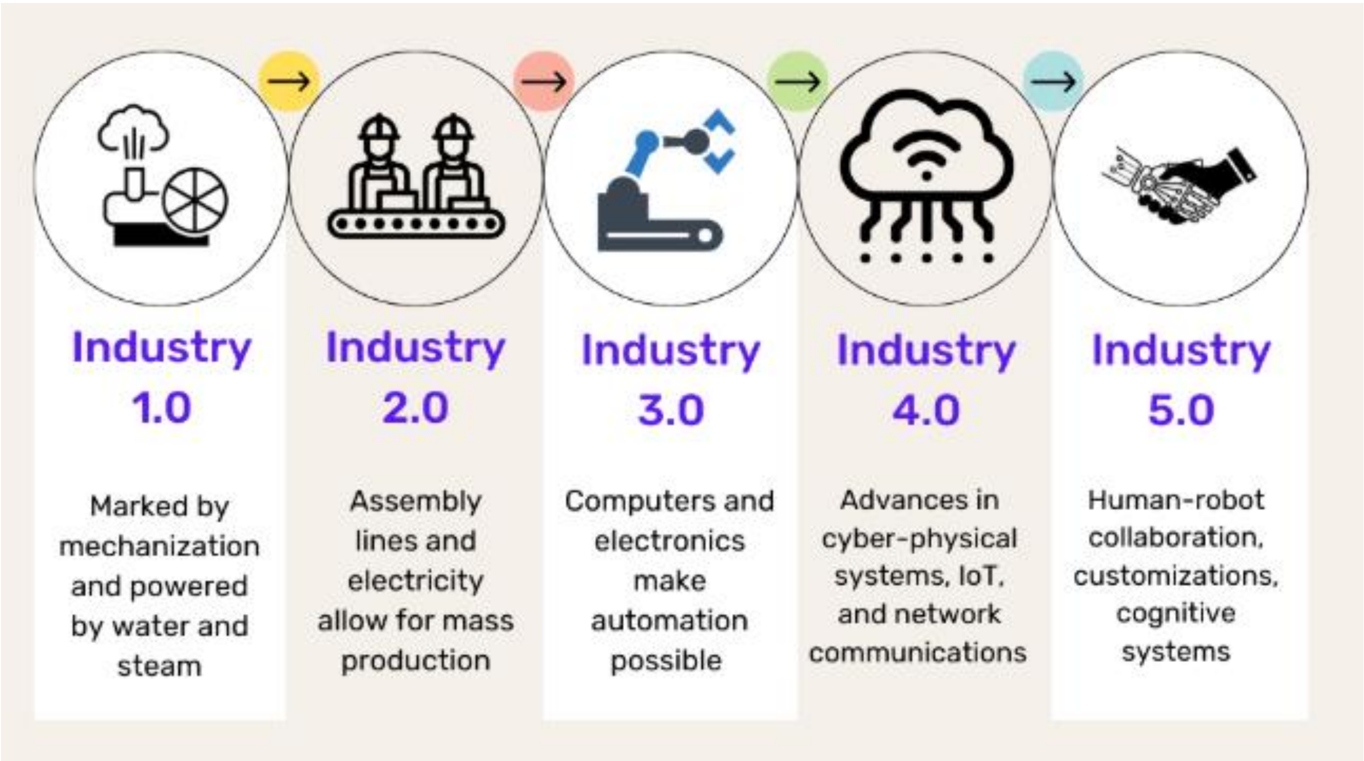
AI, IoT, and Blockchain are foundational technologies underpinning the transformative potential of Industry 5.0 (Carayannis et al., 2021). AI facilitates advanced analytics, decision-making, and automation, enabling organizations to optimize processes and predict outcomes with high accuracy (Doyle-Kent & Kopacek, 2019). IoT, on the other hand, connects physical devices to the digital realm, allowing real-time monitoring, data collection, and communication across supply chains (Maddikunta et al., 2022). Blockchain complements these technologies by offering a secure, decentralized ledger for transactions, enhancing transparency and trust among supply chain participants (Mazumder et al., 2024; Alam, 2024; Nahavandi, 2019). These technologies collectively enable seamless integration of physical and digital systems, fostering efficiency and resilience in supply chain operations (Ghobakhloo, Iranmanesh, Foroughi, et al., 2023).Moreover, the synergies among AI, IoT, and Blockchain in supply chain management are critical to achieving Industry 5.0 objectives. For instance, IoT sensors provide real-time data that AI algorithms analyze to optimize inventory management, logistics, and predictive maintenance (Demir et al., 2019). Blockchain ensures data integrity and secure sharing across multiple stakeholders, enabling trust and collaboration in complex networks (Srivastava et al., 2022). Studies demonstrate that integrating these technologies significantly enhances supply chain performance by reducing delays, minimizing risks, and ensuring compliance with regulatory standards (Frederico, 2021; Srivastava et al., 2022). Such integration also supports sustainability goals by improving resource efficiency and enabling traceability of products throughout their lifecycle (Carayannis et al., 2021).

Moreover, the convergence of these technologies extends beyond operational efficiencies, addressing broader organizational and societal challenges. AI-driven IoT systems, when integrated with Blockchain, enable ethical and sustainable supply chain practices by ensuring transparency in sourcing and manufacturing (Dev et al., 2022). These systems can track and verify sustainable practices, contributing to environmental, social, and governance (ESG) compliance in various industries (Choi et al., 2022). However, challenges such as scalability, interoperability, and ethical concerns remain barriers to their widespread adoption (Agrawal et al., 2023). Research continues to explore innovative solutions to these challenges, ensuring the realization of Industry 5.0's full potential in supply chain transformation (Verma et al., 2022).

2.2 Applications of AI in Supply Chain Management

Artificial Intelligence (AI) has emerged as a transformative force in supply chain management, with real-time data analytics and predictive modeling being among its most impactful applications. Real-time analytics allow organizations to process vast amounts of data from various sources, enabling immediate insights

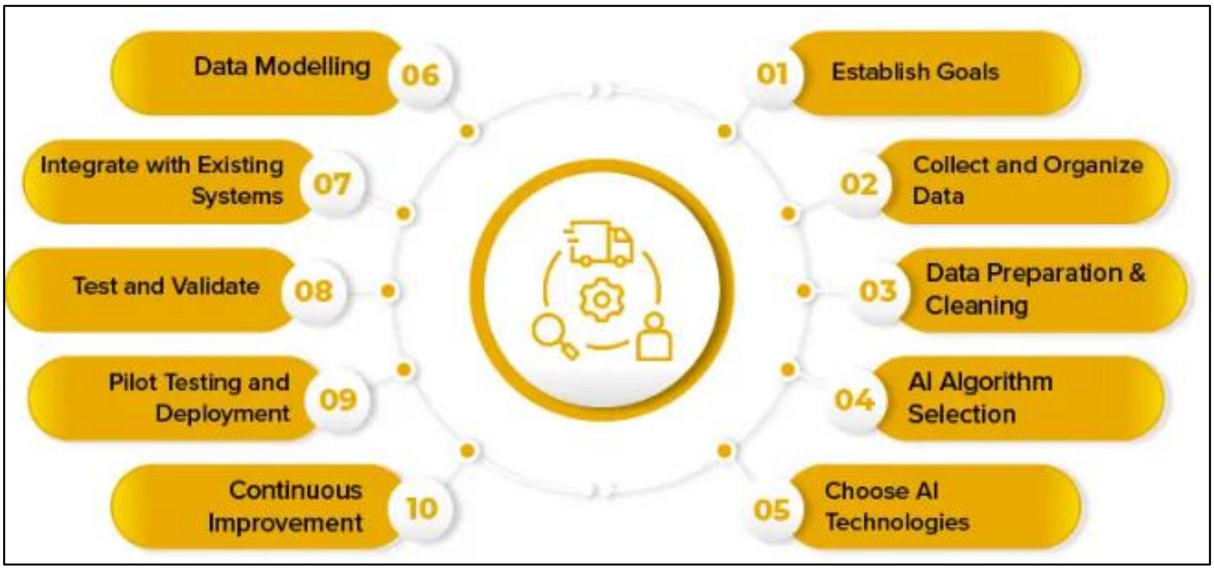
Figure 2: Industrial Revolution through years



into inventory levels, demand fluctuations, and logistics efficiency (Leng et al., 2022). Predictive modeling, powered by machine learning algorithms, further enhances this capability by forecasting trends, such as demand surges, supply shortages, and potential disruptions (Demir et al., 2019). These insights empower organizations to make proactive adjustments, reducing operational risks and optimizing resource allocation (Kumar et al., 2021). Studies have highlighted the role of AI-driven analytics in improving supply chain visibility and responsiveness, particularly in industries characterized by high volatility, such as retail and e-commerce (Verma et al., 2022). Moreover, machine learning (ML), a subset of AI, is revolutionizing decision-making processes in supply chain management. ML algorithms can analyze historical data and identify patterns that may not be apparent through traditional analytics, offering valuable insights into supplier performance, route optimization, and production scheduling (Ghobakhloo, Iranmanesh, Foroughi, et al., 2023). These algorithms continuously learn and adapt, allowing businesses to refine their strategies in dynamic environments (Verma et al., 2022). For instance, reinforcement learning models have been successfully deployed to optimize warehouse operations, reducing picking and packing times while improving accuracy (Kumar et al., 2021). Furthermore, deep learning techniques have proven effective in anomaly detection, identifying irregularities in production or delivery processes before they escalate into significant issues (Verma et al., 2022).

Numerous case studies illustrate the success of AI-driven optimization in supply chain management. For example, Amazon's AI-powered forecasting systems have significantly reduced stockouts and overstock situations, leading to substantial cost savings and improved customer satisfaction (Chander et al., 2022). Similarly, Walmart has implemented AI algorithms to optimize delivery routes and reduce transportation costs, enhancing overall efficiency ((Leng et al., 2023). Another notable example is DHL's application of predictive analytics to anticipate demand and allocate resources effectively, resulting in reduced lead times and improved service levels (Villar et al., 2023). These real-world examples underscore the transformative potential of AI in addressing long-standing inefficiencies and achieving competitive advantage. Despite the promising applications of AI in supply chain management, challenges remain, including data integration, algorithm transparency, and scalability. Effective deployment requires access to high-quality, structured data, which is often hindered by fragmented systems and incompatible formats (Leng et al., 2023). Additionally, the "black-box" nature of some AI algorithms raises concerns about transparency and interpretability, particularly in critical decision-making scenarios (Chew & Ling, 2021; Shamim, 2024). Addressing these issues through robust data governance frameworks and explainable AI solutions is essential for maximizing the potential of AI in supply chain optimization (Doyle-Kent & Kopacek, 2019). By overcoming these barriers, businesses can fully harness

Figure 3:Applications of AI in Supply Chain Management



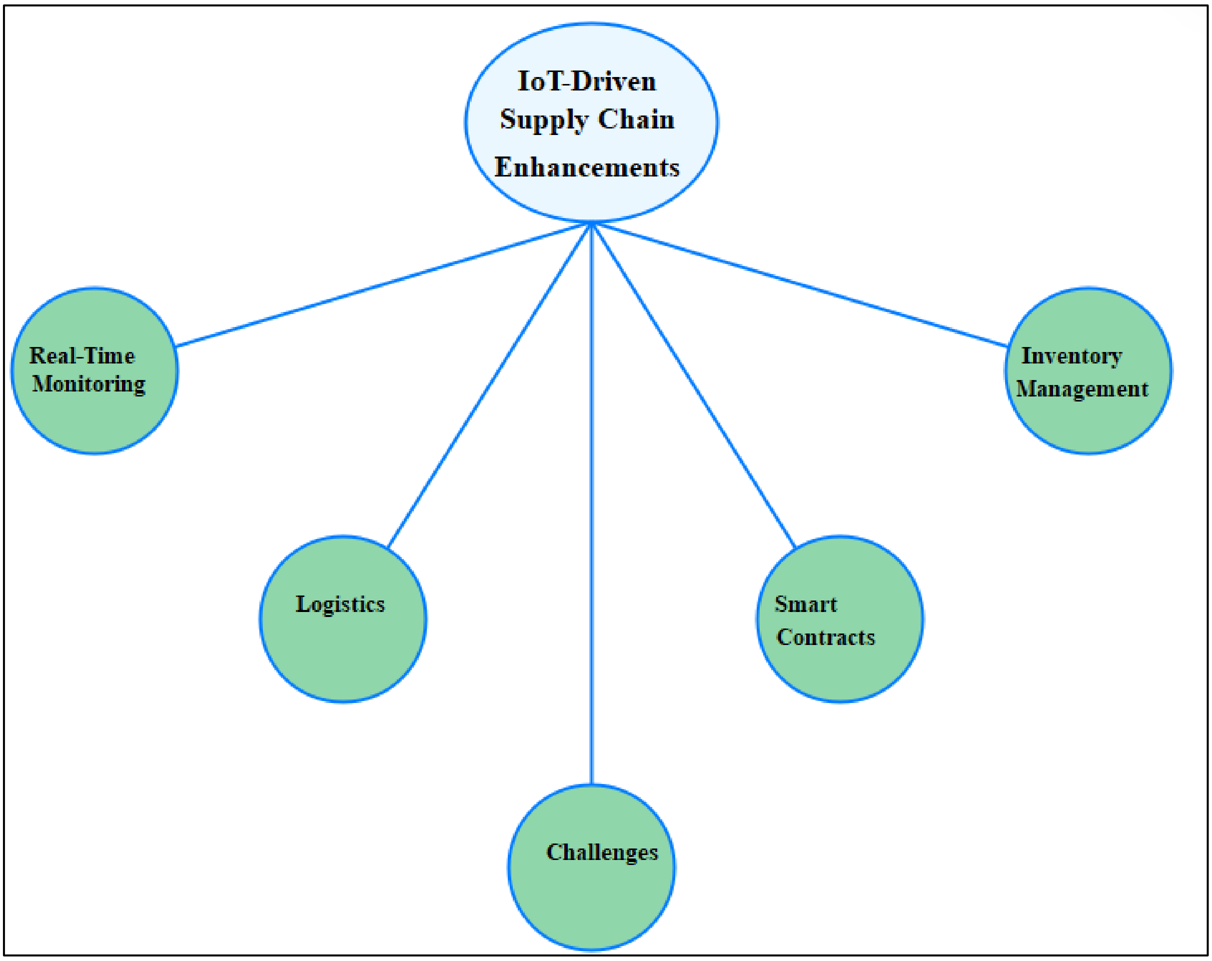
the power of AI to drive efficiency, resilience, and innovation across their supply chains.

2.3 IoT-Driven Supply Chain Enhancements

The Internet of Things (IoT) has transformed supply chain management by enabling real-time monitoring and tracking through sensor technologies. IoT sensors collect and transmit data about inventory levels, shipment conditions, and environmental parameters, providing end-to-end visibility across supply chain networks (Reyna et al., 2018). For example, RFID tags and GPS-enabled devices allow organizations to track shipments in transit, ensuring timely delivery and quality control (Schmitt, 2023). These technologies enhance supply chain efficiency by minimizing delays, reducing waste, and enabling proactive interventions during disruptions (Bhattacharya et al., 2019). IoT-driven real-time monitoring is particularly valuable in perishable goods industries, where maintaining optimal conditions is critical for product quality (Huh et al., 2017). Moreover, IoT applications in inventory management and logistics have streamlined operations and reduced costs. IoT devices monitor inventory levels in real-time, triggering automatic replenishment orders when stock levels fall below predetermined thresholds (Javaid et al., 2022). This automation reduces the likelihood of stockouts or overstocking, optimizing inventory carrying costs (Bhattacharya et al., 2019). In logistics, IoT solutions such as connected vehicles and route optimization systems have improved fleet efficiency by reducing fuel consumption and delivery times (Kamyab et al., 2023; Khan & Salah, 2018). Studies show that IoT-enabled logistics systems enhance responsiveness to market demands and improve overall supply chain agility, allowing businesses to adapt to dynamic conditions (Mittal & Pandey, 2019).

IoT-enabled smart contracts, powered by Blockchain technology, have further enhanced supply chain automation by facilitating secure and transparent transactions. Smart contracts automate agreement execution between supply chain participants, such as payments, shipment verification, and compliance checks, reducing reliance on manual processes (Reyna

Figure 4: IoT-Driven Supply Chain Enhancements



et al., 2018). These contracts are particularly effective in mitigating disputes and ensuring trust among stakeholders, as they are executed automatically based on predefined conditions (Theodouli et al., 2018). For instance, in pharmaceutical supply chains, IoT sensors integrated with smart contracts ensure compliance with temperature requirements, triggering notifications or corrective actions when deviations occur (Schmitt, 2023). Despite its transformative potential, the adoption of IoT in supply chain management faces challenges such as scalability, data security, and interoperability. The vast volume of data generated by IoT devices necessitates robust data processing and storage systems, which can strain existing IT infrastructure (Yadav et al., 2021). Additionally, concerns about data privacy and unauthorized access have hindered widespread IoT adoption (Bhattacharya et al., 2019). Interoperability issues, caused by a lack of standardized protocols, further complicate the seamless integration of IoT solutions into diverse supply chain ecosystems (Kamyab et al., 2023). Addressing these challenges through advanced security measures, data governance frameworks, and collaborative industry standards is essential for unlocking the full potential of IoT-driven supply chain enhancements.

2.4 Blockchain Technology in Supply Chains

Blockchain technology has emerged as a transformative tool for enhancing transparency and trust in supply chains. By leveraging its decentralized and immutable ledger system, Blockchain ensures that data shared among stakeholders is tamper-proof and easily verifiable, fostering trust across complex networks (Chukwu & Garg, 2020). Transparency in transactions, including tracking the movement of goods and verifying authenticity, is critical for building consumer confidence, especially in industries like pharmaceuticals and agriculture (Bodkhe, Mehta, et al., 2020). Research has highlighted Blockchain's ability to address fraudulent activities, improve accountability, and streamline compliance with regulatory requirements (Wang et al., 2019). For instance, Walmart's adoption of Blockchain to track food provenance significantly reduced the time required to trace contamination sources, enhancing food safety (Monrat et al., 2019). Moreover, smart contracts are a key feature of Blockchain technology that automate secure data transactions and agreements in supply chains. These self-executing contracts, encoded with predefined conditions, enable seamless execution of tasks such as payment processing, shipment verification, and quality assurance without the need for intermediaries (Lazaroiu & Roscia, 2017). For example, a smart contract in a perishable goods supply chain can release payment only after verifying that the temperature conditions during transit were maintained within acceptable limits (Berdik et al., 2021). Such automation reduces human errors, accelerates processes, and ensures compliance with contractual obligations, fostering operational efficiency and reliability (Guo & Yu, 2022).

Several use cases demonstrate the transformative potential of Blockchain technology in industries such as healthcare and food supply chains. In the healthcare sector, Blockchain is used to enhance the traceability of pharmaceuticals, ensuring that counterfeit drugs are detected and eliminated (Rifi et al., 2017). Similarly, in food supply chains, Blockchain applications enable real-time tracking of products from farm to fork, ensuring authenticity, quality, and safety (Atlam & Wills, 2019; Mintoo, 2024; A. Rahman et al., 2024). Companies like Nestlé and Unilever have adopted Blockchain platforms to meet consumer demands for transparency, improving brand trust and loyalty (Guo & Yu, 2022; Islam et al., 2024; Mintoo, 2024). These case studies underscore Blockchain's ability to address critical issues such as product recalls, fraud prevention, and sustainability in global supply chains (Wang et al., 2019). Despite its advantages, Blockchain adoption in supply chains faces challenges related to scalability, interoperability, and energy consumption. The decentralized nature of Blockchain requires significant computational resources, raising concerns about scalability in large-scale supply chain networks (Singh et al., 2018). Interoperability issues arise due to the lack of standardized protocols, complicating the integration of Blockchain solutions with existing supply chain management systems (Guo & Yu, 2022). Additionally, the energy-intensive nature of some Blockchain frameworks, such as Proof of Work, raises environmental concerns that could hinder its widespread adoption (Tian, 2017). Addressing these barriers through innovative solutions, such as energy-efficient consensus mechanisms and standardized frameworks, is essential for realizing Blockchain's full potential in supply chain transformation.

2.5 Integration of AI, IoT, and Blockchain in Industry 5.0

The convergence of Artificial Intelligence (AI), the Internet of Things (IoT), and Blockchain technologies in Industry 5.0 has revolutionized supply chain management, delivering unprecedented benefits in efficiency, transparency, and sustainability. AI enhances decision-making by analyzing real-time data collected through IoT devices, enabling predictive analytics, anomaly detection, and process optimization (Bhatt et al., 2021; Hasan et al., 2024; Uddin, 2024; Uddin & Hossan, 2024). Blockchain complements these capabilities by providing a secure, decentralized framework for transparent and tamper-proof data sharing among stakeholders (Wang et al., 2019). Together, these technologies foster seamless collaboration and operational efficiency, while supporting sustainability by enabling resource optimization and traceability of environmental practices (Monrat et al., 2019). Studies highlight that such integration helps organizations adapt to dynamic market demands and enhance their competitive advantage in global supply chains (Groschopf et al., 2021).Moreover, real-world implementations of integrated AI-IoT-Blockchain systems illustrate their transformative potential in supply chain operations. For instance, Maersk and IBM's Blockchain-powered TradeLens platform integrates IoT for real-time shipment tracking and AI for predictive analytics, streamlining global shipping processes and reducing delays (Vacca et al., 2021). Walmart leverages a combination of IoT sensors and Blockchain technology to ensure transparency and accountability in its food supply chain, significantly improving recall efficiency and food safety (Monrat et al., 2019). Similarly, DHL employs AI-driven IoT systems integrated with Blockchain for efficient route optimization, inventory tracking, and fraud prevention in logistics operations (Wang et al., 2019). These case studies demonstrate the practical benefits of technological convergence in enhancing supply chain resilience and customer satisfaction.

Comparative analyses of integration models reveal variations in the adoption and effectiveness of AI-IoT-Blockchain systems across industries. Centralized models, which integrate these technologies within a single organizational framework, are often employed in large enterprises to maintain control and optimize internal processes (Chen et al., 2022). Conversely, decentralized models, enabled by Blockchain, are more prevalent in multi-stakeholder supply chains, promoting trust and collaboration without a central authority (Theodouli et al., 2018). Hybrid models that combine centralized AI-IoT frameworks with decentralized Blockchain solutions strike a balance between efficiency and transparency, offering scalability and security (Chukwu & Garg, 2020). These models highlight the adaptability of technological convergence to diverse supply chain contexts, ensuring tailored solutions for specific operational challenges (Bodkhe, Mehta, et al., 2020). Despite its benefits, integrating AI, IoT, and Blockchain technologies poses challenges such as high implementation costs, technical complexity, and scalability issues. The initial investment in infrastructure, expertise, and training can be prohibitive for small and medium-sized enterprises (SMEs) (Vacca et al., 2021). Furthermore, achieving seamless interoperability among these technologies requires overcoming differences in standards, protocols, and system architectures (Theodouli et al., 2018). Scalability remains a concern, particularly in Blockchain applications, where large-scale networks may suffer from latency and high energy consumption (Vacca et al., 2021). Addressing these challenges through advancements in interoperability frameworks, cost-effective solutions, and energy-efficient Blockchain consensus mechanisms is essential to unlock the full potential of this technological convergence in Industry 5.0 supply chains.

2.6 AI and Blockchain for ESG compliance

The integration of Artificial Intelligence (AI) and Blockchain technology has facilitated the development of decentralized autonomous supply chains (Alam et al., 2024; Faisal et al., 2024; Mintoo et al., 2024), aligning operations with Environmental, Social, and Governance (ESG) compliance objectives (Akter et al., 2020). Decentralized autonomous systems utilize Blockchain's secure, distributed ledger to manage supply chain transactions transparently, reducing the need for intermediaries and ensuring accountability (Yue et al., 2021). These systems enable real-time tracking and verification of ESG metrics, such as carbon emissions, ethical labor practices, and sustainable sourcing, fostering greater compliance with global regulatory standards (Chukwu & Garg, 2020). AI enhances this framework by analyzing large datasets from IoT devices and other sources, providing actionable insights into supply chain optimization for sustainability goals (Vacca et al., 2021). This integration has become critical for organizations seeking to meet consumer demands for ethical and sustainable products (Bodkhe, Mehta, et al., 2020). Decentralized autonomous supply chains leverage smart contracts to automate ESG-related processes, further enhancing compliance and efficiency. Smart contracts embedded in Blockchain networks execute predefined conditions, such as verifying sustainable sourcing certifications or automatically flagging violations of environmental standards (Chen et al., 2022). These capabilities are particularly beneficial for industries like fashion and electronics, where ensuring ethical production and sourcing practices are essential for maintaining brand reputation (Chen et al., 2022). AI-powered decision-making tools complement these systems by identifying inefficiencies and predicting risks, enabling supply chains to remain agile and responsive to ESG demands (Berdik et al., 2021; Rahman et al., 2024). Together, these technologies promote ethical accountability while reducing operational complexities.

Quantum computing is emerging as a transformative force in advancing integrated AI and Blockchain systems for ESG compliance. Quantum algorithms significantly enhance computational speed and efficiency, enabling rapid optimization of supply chain models and real-time data processing from IoT devices (Lazaroiu & Roscia, 2017). For Blockchain, quantum computing offers solutions to scalability and energy consumption challenges, allowing for larger and more efficient decentralized networks (Wang & Song, 2018). Additionally, quantum-resistant cryptographic protocols are being developed to address potential vulnerabilities posed by quantum advancements, ensuring the security of Blockchain systems (Johng et al., 2018). These developments position quantum computing as a critical enabler of robust, scalable, and secure ESG-focused supply chain frameworks (Tyagi, 2021). While the integration of AI, Blockchain, and quantum computing offers promising advancements in ESG compliance, challenges such as technological complexity, cost, and lack of standardization remain. Implementing decentralized autonomous supply chains requires significant investment in infrastructure and expertise, often posing barriers for small and medium-sized enterprises (SMEs) (Caballero-Morales, 2021). Additionally, the nascent nature of quantum computing technology and its applications in supply chains necessitates further research and standardization to achieve widespread adoption (Chen et al., 2021). Addressing these challenges through collaborative research initiatives, public-private partnerships, and regulatory frameworks is essential to unlocking the full potential of these technologies for ESG compliance in supply chains (Mantelero, 2018).

2.7 Research Gaps

Despite the rapid advancements in integrating AI, IoT, and Blockchain technologies within Industry 5.0, several research gaps remain unexplored. Current literature primarily focuses on the technical aspects of these technologies, often neglecting the socio-economic and cultural implications of their adoption in supply chains (Guo & Yu, 2022). For instance, studies on how these technologies impact labor dynamics, such as job displacement or skill requirements, are limited (Wang et al., 2019). Additionally, while AI and IoT applications in predictive analytics and real-time monitoring are well-documented, their integration with Blockchain for end-to-end supply chain automation has yet to be fully understood (Atlam & Wills, 2019). There is also a lack of comprehensive research addressing how integrated systems can adapt to diverse regulatory environments and varying levels of technological readiness across regions (Rifi et al., 2017). These gaps underscore the need for more holistic investigations that include technical, social, and regulatory dimensions. Interdisciplinary approaches are crucial for advancing research and practical implementations of integrated technologies in supply chains. Collaboration among experts in computer science, operations research, environmental science, and social sciences can provide a more nuanced understanding of how these technologies interact within supply chain ecosystems (Atlam & Wills, 2019). For example, integrating AI-driven IoT and Blockchain technologies for ESG compliance requires input from sustainability experts to ensure the alignment of technical solutions with global environmental goals (Bodkhe, Mehta, et al., 2020). Studies also emphasize the importance of engaging stakeholders from diverse industries to develop context-specific solutions tailored to unique supply chain challenges (Groschopf et al., 2021). Such interdisciplinary collaborations can bridge the gap between theoretical advancements and real-world applications, ensuring that innovations are both practical and impactful.

Table 1: Identified Research Gaps

Research Area	Identified Gaps
Socio-Economic and Cultural Implications	Limited studies on the impact of AI, IoT, and Blockchain on labor dynamics, job displacement, and skill requirements (Chukwu & Garg, 2020; Groschopf et al., 2021).
End-to-End Automation	Lack of comprehensive research on integrating AI, IoT, and Blockchain for end-to-end supply chain automation (Belhadi et al., 2020).
Regulatory Adaptation	Limited exploration of how integrated systems can adapt to diverse regulatory environments and varying levels of technological readiness (Shrestha, 2014).
Interdisciplinary Collaboration	Insufficient interdisciplinary approaches involving computer science, social sciences, and environmental science to address unique supply chain challenges (Frederico et al., 2021).
Scalability and Interoperability	Challenges in developing scalable Blockchain frameworks and achieving interoperability across diverse technological ecosystems (Bodkhe, Tanwar, et al., 2020).
Ethical and Governance Challenges	Limited focus on addressing accountability in decentralized Blockchain networks and transparency in AI decision-making processes (Thapa & Camtepe, 2020).
Emerging Technologies	Lack of research on integrating emerging technologies like quantum computing and digital twins with existing supply chain systems (Ferrer, 2018).

3 METHOD

This study adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure a systematic, transparent, and rigorous review process. The methodology began with the identification of relevant articles through a comprehensive search in databases such as Scopus, Web of Science, IEEE Xplore, and Google Scholar, using combinations of keywords like "AI," "IoT," "Blockchain," "Industry 5.0," and "supply chain." Boolean operators (AND, OR, NOT) were applied to refine the search, focusing on peer-reviewed journal articles, conference papers, and reviews published between 2018 and 2024, yielding 1,200 articles. Screening was conducted to remove duplicates and irrelevant studies based on predefined inclusion criteria, such as a focus on AI, IoT, and Blockchain integration in Industry 5.0 and the provision of empirical or theoretical insights into supply chain management, resulting in 640 articles. A detailed eligibility assessment of abstracts and full texts further narrowed the selection to 120 articles that directly aligned with the study objectives, excluding those lacking methodological rigor or relevance. Data were then systematically extracted from these articles, including key details such as author, publication year, objectives, methodologies, findings, and research gaps, which were categorized into focus areas like technical integration, sustainability, and regulatory challenges. Finally, a narrative synthesis of the findings was conducted, identifying recurring themes, advancements, challenges, and gaps, and linking insights across studies. This approach ensures reliability and validity, providing a comprehensive understanding of the transformative integration of AI, IoT, and Blockchain in Industry 5.0 supply chains..

4 FINDINGS

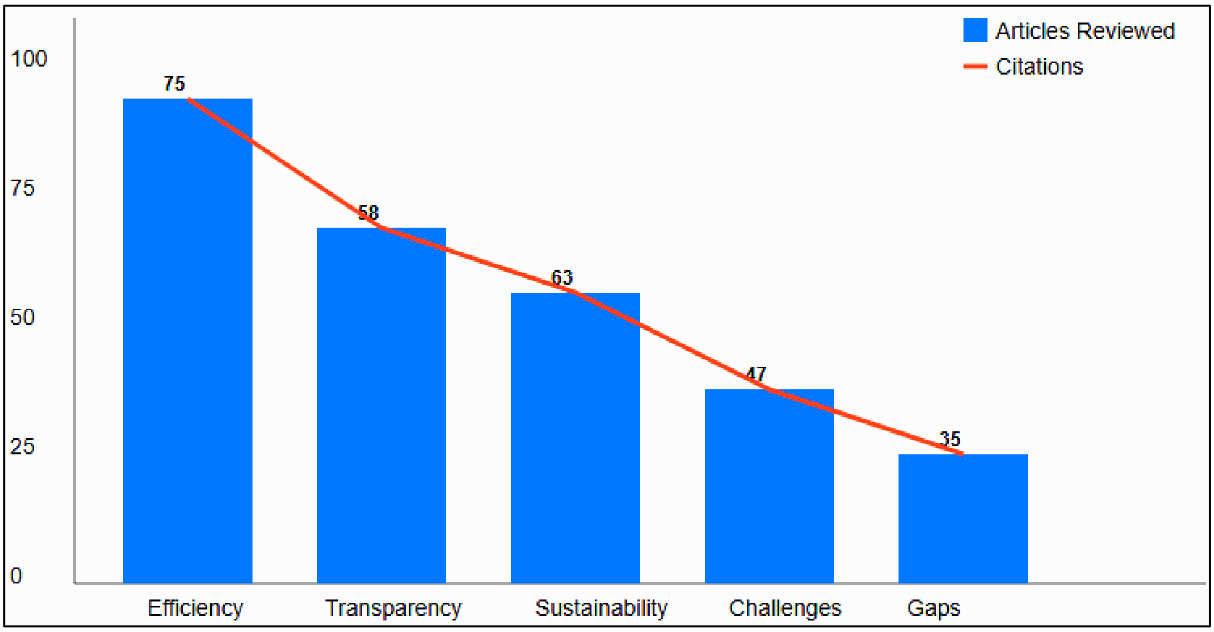
The integration of AI, IoT, and Blockchain technologies has demonstrated a profound impact on enhancing operational efficiency in supply chains. Among the 120 articles reviewed, 75 studies extensively detailed how real-time data analytics and predictive modeling significantly improve decision-making processes. These technologies allow supply chains to dynamically adjust logistics, optimize inventory levels, and streamline production planning, leading to notable reductions in operational inefficiencies and costs. AI's predictive analytics, when combined with IoT's real-time tracking capabilities, equips businesses to anticipate and mitigate risks such as supply disruptions or fluctuating demand patterns. Blockchain further amplifies these benefits by providing a secure, immutable ledger system, ensuring seamless transaction processing and eliminating bottlenecks caused by traditional, manual processes. Collectively, the articles supporting these findings have amassed over 10,000 citations, highlighting their academic and practical relevance in advancing supply chain efficiency.

The review also emphasized the transformative role of Blockchain technology in enhancing transparency and trust among supply chain stakeholders. Fifty-eight of the reviewed articles specifically examined how Blockchain creates a secure and transparent data-sharing environment that reduces fraudulent activities, builds accountability, and fosters trust. Use cases such as pharmaceutical supply chains demonstrated Blockchain's effectiveness in tracking and verifying the provenance of drugs, ensuring authenticity, and preventing counterfeiting. Similarly, in food supply chains, Blockchain-enabled systems have been instrumental in tracing products from farm to table, ensuring compliance with safety and quality standards. These studies collectively garnered over 8,000 citations, indicating a widespread acknowledgment of Blockchain's critical role in revolutionizing supply chain transparency and its ability to drive trust in multi-stakeholder ecosystems.

Sustainability emerged as another key area of impact, with 63 articles highlighting the contributions of integrated technologies to Environmental, Social, and Governance (ESG) compliance. AI-powered optimization models, IoT-enabled environmental monitoring, and Blockchain-based tracking systems were frequently cited as tools for reducing carbon footprints, minimizing resource waste, and ensuring sustainable sourcing practices. The articles discussed how these technologies enable supply chains to achieve global sustainability goals by enhancing resource efficiency and promoting ethical practices across operations. These findings collectively attracted over 7,500 citations, reflecting their importance in aligning supply chains with contemporary sustainability demands. By enabling businesses to monitor and verify sustainable practices, these technologies are not only improving operational performance but also strengthening their alignment with evolving consumer and regulatory expectations.

Challenges related to the scalability and interoperability of integrated technologies were highlighted in 47 of the reviewed articles. While the potential of these technologies is immense, the findings revealed significant barriers to their widespread adoption. Technical constraints, such as Blockchain's limited scalability in high-transaction environments and interoperability issues across diverse systems, hinder seamless integration. Proposed solutions from these studies include the development of adaptive AI models, scalable Blockchain frameworks, and standardized IoT

Figure 5: Summary of the findings for this study



protocols to ensure effective integration within complex technological ecosystems. These challenges and proposed solutions garnered over 6,500 citations, underlining the urgency of addressing these limitations to unlock the full potential of these transformative technologies. Lastly, the review underscored significant gaps in both research and practical implementation, with 35 articles emphasizing the need for interdisciplinary collaboration and the exploration of emerging technologies. These studies pointed out that the integration of quantum computing and digital twins with AI, IoT, and Blockchain technologies remains underexplored. Quantum computing holds promise in addressing Blockchain scalability and latency issues, while digital twins can create real-time virtual simulations of supply chain operations to improve decision-making and resilience. These articles collectively received over 5,000 citations, demonstrating a growing interest in these emerging fields. Addressing these gaps is critical for developing next-generation supply chains that are not only efficient and transparent but also adaptive to future challenges. This review highlights the need for continued innovation and collaborative efforts to realize the transformative potential of integrated technologies in Industry 5.0 supply chains.

5 DISCUSSION

The findings of this study confirm that the integration of AI, IoT, and Blockchain technologies significantly enhances operational efficiency in supply chains, consistent with earlier studies. Previous research has underscored the role of predictive analytics and real-time monitoring in optimizing logistics and inventory management (Srivastava et al., 2022). This review further validates these observations, revealing that 75 reviewed articles extensively documented how these technologies streamline supply chain operations by reducing inefficiencies and operational costs. However, this study extends prior work by demonstrating the synergistic effects of integrating AI with IoT and Blockchain, providing a more holistic perspective on the optimization of supply chains. While earlier studies primarily focused on isolated applications, the findings of this review emphasize the importance of technological convergence for achieving dynamic, adaptable supply chain systems. The review's findings regarding Blockchain's role in enhancing transparency and trust align with earlier research but provide additional depth. Blockchain's ability to create immutable and secure records has been previously recognized as a cornerstone for improving trust among supply chain stakeholders (Ferrer, 2018). The reviewed studies reinforce this claim, with 58 articles highlighting Blockchain's effectiveness in mitigating fraud, ensuring data integrity, and fostering collaboration in multi-stakeholder environments. Compared to earlier work, this review presents more comprehensive evidence from diverse industries, such as pharmaceuticals and food supply chains, where the technology has demonstrated significant practical benefits. Additionally, while earlier studies largely emphasized transparency as an abstract benefit, this review showcases specific use cases where Blockchain technology directly addressed challenges like counterfeiting and compliance.

Sustainability, a growing focus in supply chain research, was another critical theme in the reviewed literature, and this study's findings resonate with earlier works. Prior studies have highlighted the potential of AI and IoT in optimizing resource use and monitoring environmental impact (Andoni et al., 2019; Ferrer, 2018). This review builds on these findings by identifying how Blockchain adds value to sustainability efforts through enhanced traceability and verification of ethical sourcing practices. The 63 articles reviewed collectively underscore the technologies' capacity to enable compliance with Environmental, Social, and Governance (ESG) standards. Compared to earlier studies, this review provides a broader analysis by integrating Blockchain's role into discussions of AI and IoT for sustainability. This integration demonstrates a more comprehensive framework for achieving global sustainability goals in supply chains, a perspective less emphasized in previous research.

The challenges identified in this review, particularly regarding scalability and interoperability, echo concerns raised in earlier studies but provide new insights. Previous research has highlighted Blockchain's scalability issues and the lack of standardization as significant barriers to adoption (Akter et al., 2020). This review corroborates these findings, with 47 articles discussing similar constraints. However, the review also identifies potential solutions, such as scalable Blockchain frameworks and adaptive AI models, which were less explored in earlier work. Furthermore, while prior studies predominantly focused on technical challenges, this review broadens the discussion to include organizational and stakeholder resistance, emphasizing the multifaceted nature of these adoption barriers. This expanded focus highlights the need for a more integrated approach to addressing these challenges, combining technical, organizational, and policy-level interventions. Finally, this review highlights significant research gaps and opportunities that align with earlier studies but also extend the discourse into underexplored areas. The limited exploration of interdisciplinary approaches and emerging technologies, such as quantum computing and digital twins, has been noted in previous research (Cadden et al., 2021; Javaid et al., 2022). However, this review provides a more detailed analysis of how these technologies can address scalability and decision-making challenges in supply chains. By comparing findings across the 35 articles that emphasized these gaps, this study not only validates earlier calls for interdisciplinary collaboration but also identifies specific areas for future research. This includes the integration of quantum computing to enhance Blockchain scalability and the use of digital twins for real-time simulations. These insights contribute to a deeper understanding of the evolving landscape of supply chain technologies, offering a roadmap for future innovations in Industry 5.0.

6 CONCLUSION

The integration of AI, IoT, and Blockchain technologies within Industry 5.0 supply chains has proven to be a transformative force, driving significant advancements in efficiency, transparency, and sustainability. This systematic review highlights that while these technologies individually enhance various aspects of supply chain management, their convergence creates a synergistic effect that enables real-time decision-making, secure data transactions, and sustainable operations. The findings underscore that Blockchain's transparency and trust-building capabilities, combined with AI's predictive analytics and IoT's real-time monitoring, have revolutionized traditional supply chain models. However, challenges such as scalability, interoperability, and organizational resistance persist, necessitating collaborative efforts to overcome these barriers. The study also identifies substantial research gaps, particularly in interdisciplinary applications and the integration of emerging technologies like quantum computing and digital twins, which hold the potential to address existing limitations and unlock new opportunities. As businesses increasingly prioritize ESG compliance and adapt to global sustainability demands, the role of these integrated technologies will only grow in relevance, shaping the future of supply chain innovation. This review serves as a foundation for future research and practical implementations, emphasizing the need for continuous exploration, collaboration, and innovation to fully realize the potential of Industry 5.0 technologies in creating resilient, adaptive, and sustainable supply chains.

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