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INTEGRATING AI, BLOCKCHAIN, AND IOT FOR SUSTAINABLE AND RESILIENT GLOBAL SUPPLY CHAINS

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Abstract
Global supply chains are increasingly exposed to systemic risks arising from geopolitical instability, pandemics, climate change, and evolving regulatory demands. These risks highlight the need for efficient, resilient, transparent, and sustainable supply chains. Recent advances in artificial intelligence (AI), blockchain, the Internet of Things (IoT), and sustainability practices are synthesized in this review, providing an integrated approach of these factors reshaping the supply chain management. The analysis shows that AI enhances forecasting, logistics, and risk management through predictive and adaptive capabilities; blockchain strengthens transparency, trust, and traceability via decentralized and immutable records; IoT delivers real-time monitoring and operational visibility; and sustainability practices anchor these innovations within ecological and social imperatives such as green logistics, circular economy, and ethical sourcing. Case studies from industries including agriculture, retail, and manufacturing demonstrate that while individual technologies yield incremental benefits, their integration produces superior outcomes in efficiency, accountability, and environmental performance. However, significant barriers remain that include high implementation costs, interoperability challenges, cybersecurity vulnerabilities, organizational resistance, and social concerns such as labor displacement constrain widespread adoption. The review identifies gaps in addressing social sustainability, cross-regional interoperability, and governance frameworks for autonomous decision-making. Future developments, including digital twins, quantum computing, Web3, and Industry 5.0 promise further transformation, but their success will depend on harmonized policy, ethical oversight, and inclusive adoption. This review concludes that holistic integration of digital technologies with sustainability principles is essential to build supply chains that are future-ready, resilient, and aligned with global sustainability goals.

INTRODUCTION

Global supply chains are turning into even more complicated networks, crossing borders and sectors and juggling between cost-effectiveness and service quality. These systems, however, have been strained to unprecedented levels in the past decade. Trade wars and sanctions, as well as armed conflicts, are geopolitical risks that have interfered with established goods paths, fueling uncertainty in the

sourcing and production (Rasshyvalov *et al.*, 2024). These vulnerabilities were increased by the COVID-19 pandemic that caused systemic deteriorations in logistics, labor supply, and demand patterns, highlighting the constraints of efficiency-focused, just-in-time models (Samson, 2020; Xu *et al.*, 2023). Meanwhile, the increase in the intensity of extreme weather events, the endangering of important infrastructure and the maintenance of supply chains, and an increase in the tightening of regulatory regimes around the world in the context of climate change require quantifiable progress toward the reduction of carbon and resilience (Nnaji *et al.*, 2024). All these disruptions indicate a key paradox: supply chains are required to be both lean and cost-efficient and at the same time agile, resilient, and sustainable.

Sustainability practices and digital technologies, on their part have emerged as the radical enablers of next-generation supply chain. AI assists in preemptive demand predicting, rational logistics and proactive risk control in a more intensive way enabling firms that have the data-driven flexibility in volatile markets (Nweje and Taiwo, 2025). By blockchain, the factor of trust, transparency, and traceability in multi-tier networks is enhanced with decentralization and immutability (Baranidharan *et al.*, 2025). IoT does enhance the sphere of visibility, as it is followed by the introduction of intelligence to the assets that will enable the government of the real-time monitoring, preventive maintenance, and more cost-effective functioning (Junejo *et al.*, 2023). Distributed in the same wave as these technological transformations, the imperative to be sustainable in the international system, characterized by the Paris Agreement, EU Green Deal or the Sustainable Development Goals, drives organizations to green logistics and circular economy models and ethical sourcing policies (Karaman *et al.*, 2024). They can no longer be an option: such agendas condition the competitive and regulatory environment in which global companies are currently operating.

The use of the intersectoral approach proves to be rather undesired in this respect. Despite separate studies on AI, blockchain, IoT and sustainability, there are scarce literature to bring these 4 areas together, so that transformation can be carried out holistically. The contribution of this review therefore works in three directions. In the first place, it critically examines the trends in AI, blockchain, IoT, and sustainability indicating strategic alliances and limitations of the approaches described in the scholarly and practice-based literature related to axiomatic controversies. Second, it explores the integration pathways and case-studies of successful implementation that would reflect the practical benefits and difficulties of joint adoption across such sectors as agriculture, retail and manufacturing sectors. Third, it discusses barriers and gaps in research that are yet to be addressed such as the prohibitive cost of adoption and interoperability issues to realms little researched in diving into social sustainability as well as global misalign Hence enough it indicates areas under study that have not yet been cleared yet.

This review has indicated that digital and sustainable integration is one of the paths toward finding resilience and more to the competitive advantage in the dim future by aligning technological innovation with the demands of sustainability. The findings portray a composite agenda to scholars, practitioners and policymakers in developing resilient, transparent and sustainable supply chains in the face of growing globally generated uncertainty.

1. Methodology

The systematic literature synthesis methodology is applied here to address the intersection point between the digital technologies of artificial intelligence (AI), blockchain and the Internet of
Things (IoT) and sustainability-focused supply chain practice. Sources were located through the use of academic databases including Scopus, Web of science, IEEE Xplore and ScienceDirect, and some industry-based reports and policy documents. The inter-search strategy entailed a search by using the association of the following terms: AI in supply chain, blockchain transparency, IoT logistics, green logistics, circular economy and sustainable supply chain management.

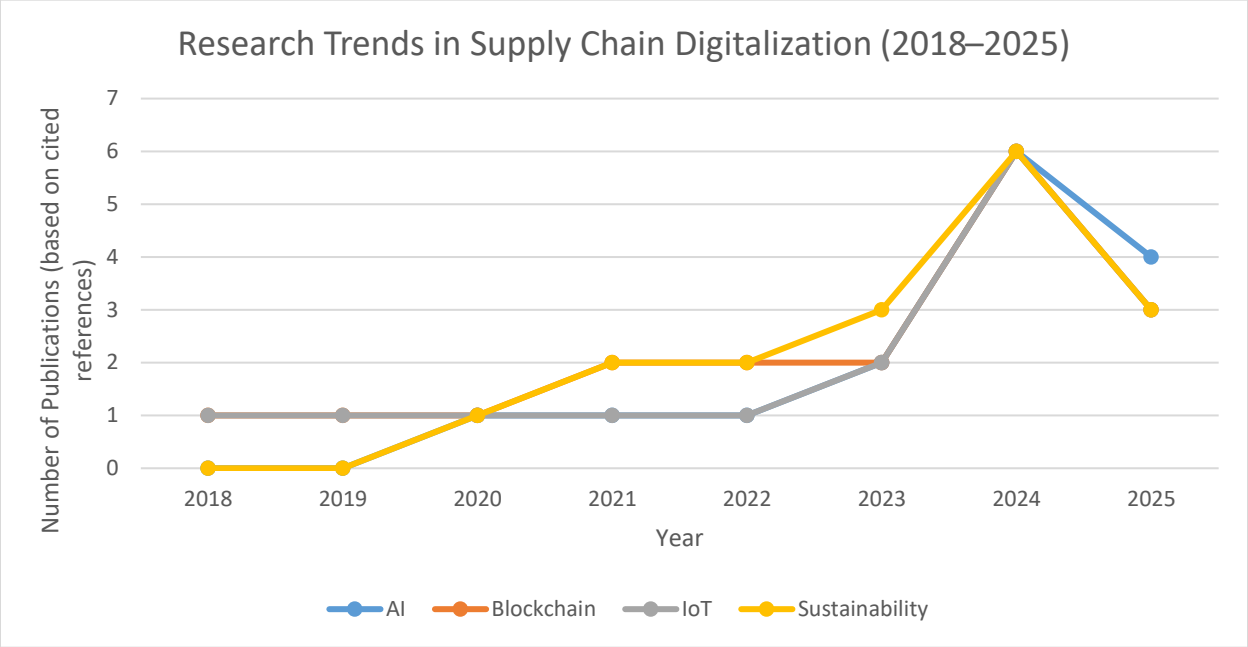


Figure I: Research Trends in Supply Chain Digitalization (2018–2025)

A narrowing down of the inclusion coefficients to include peer-reviewed journal articles, conference proceedings, and high-quality practitioner studies was also done, selected to be published between 2018 to 2025 and addressing the foundational insights as well as the new developments. Older seminal works were included, important to provide context in the development of such concepts as risk management and sustainable innovation. The final dataset of over 200 sources were analysed thematically to determine the benefits, challenges, pathways of integration and future directions.

The synthesis followed three principles. First the analysis was geared towards comparative insights through the analysis of studies and it placed emphasis on the convergences, divergences and gaps in the research as compared to summary. Second, it was thematic in that cross-disciplinary supply chain transformation crosscuts technology, management, and area of sustainability. Third, practical significance of the research was also considered, such as explanatory and illustrative case studies of the practical implementations of the discussed technologies.

The isometric will turn the review into representation of the existing body of scholarly knowledge and a source of practical information to those practitioners and policy makers who are venturing in the process of digital-sustainable transformation of planetary supply chains.

2. AI in Supply Chains

The artificial intelligence (AI) concept has taken the basis of the supply chain digitalization as businesses can transition to a more predictive and dynamic style of management. AI provides high-level forecasting, logistic optimization, and risk evaluation capabilities

offered through machine learning, deep learning and natural language processing, which makes it more efficient and resilient.

3.1. Demand Forecasting and Predictive Analytics

Given some historical data, market predictors, or, even weather, the algorithms applicable to AI calculate demand forecasts at a high level of accuracy (Okeleke *et al.*, 2024; Nweje and Taiwo, 2025). Unlike the traditional statistical procedures, these models find the seemingly non-compromising correlations among complex data, and in constant flux with new data, which lends it elasticity in the modern unstable markets. The fact that AI lessens stockouts and overstocking through fewer errors in predictions will reduce the costs of maintaining inventory and boosted customer satisfaction (Abhulimen and Ejike, 2024; Rane *et al.*, 2024). Flexibility is also encouraged by the generative AI, and it also allows flexible decision-making in rapidly changing circumstances (Aishwarya Shekhar, 2023; Yandrapalli, 2023).

3.2. Logistics and Inventory Optimization

AI is used to facilitate the management of logistics by minimizing transportation routes, considering the current traffic, the weather, and delivery schedules to minimize fuel consumption and increase the speed of delivery (Adesoga *et al.*, 2024). Robotic process automation driven by AI is used to enhance the processing of orders, scheduling, and material handling in warehouses, enhancing the precision and lowering the costs of operations (Adesoga *et al.*, 2024). In the case of inventory, the AI-based replenishment systems will automatically regulate the stock quantity based on the demand cues to achieve leaner operations and waste reduction (Jubair, 2025; Rane *et al.*, 2024).

3.3. Risk Management and Supplier Selection

AI also has a pivotal role to play in increasing supply chain resilience. Predictive analytics detect the events that might interrupt operations by tracking the indicators of geopolitical, economic, and environmental risks, which present proactive mitigation measures (Sodiya *et al.*, 2024). The evaluation of supplier performance and market conditions based on AI will reinforce the creation of stronger supplier networks, decrease the reliance on the weak nodes (Rane *et al.*, 2024). Embedded into blockchain, AI will be able to reinforce traceability and secure ethical sourcing, delivering transparency that goes through multi-tier networks (Rane *et al.*, 2024).

3.4. Benefits and Challenges

The advantages of the AI implementation in the supply chains are simply overwhelming, such as cost reduction, enhanced agility, and customer service. However, the adoption is related to impediments. You need the data quality and reliability requirement and some of the challenges that could face various organizations is their fragmented systems limiting interoperability (Nweje and Taiwo, 2025). The issue posed by an ethical perception, at best, such as, algorithmic discrimination and labour displacement compounds implementation, necessitating governance structures that create efficiencies and social responsibility as a balance.

3. Blockchain in Supply Chains

The blockchain technology has been linked to high rate of popularity in order to enhance the supply chains in the world in the context of transparency, security and trust. Its key features comprise the features of decentralization, embrasibility and real-time information auger substantive challenges of frauds, obscurity and inefficiency within the multi-tier networks.

4.1. Transparency and Traceability

At its scales, blockchain provides a distributed registry, which can be seen by anyone and, thus, none of its participants can produce or hide the information (Baranidharan *et al.*, 2025; Çodur and Erkayman, 2025). Immutability means that the transactions registered cannot be modified at all after registration and it offers a history of the procurements, production and distributions. The capabilities tend to matter particularly in industries that are more vulnerable such as food, agriculture, and pharmaceutical, where provenance and authenticity are the hotspots of safety-quality assurance (Adewusi *et al.*, 2023; Madumidha *et al.*, 2019). The data sharing in the real-time also improves accountability, which enables the

stakeholders to identify the delays, diversions, or quality problems when they occur (Ran *et al.*, 2024).

4.2. Fraud Reduction and Secure Transactions

Cryptographic functions of blockchain can diminish the intent to alter and manipulate data and commit financial wrongdoings. Combining with advanced analytics, blockchain will allow ongoing monitoring of financial transactions and in the process, anomalies can be identified at an early stage (Kokogho *et al.*, 2025). In decentralized finance, blockchain ensures a high level of protection in peer-to-peer transactions that do not involve intermediaries, saving costs and enhancing privacy (Bakare *et al.*, 2024). In institutional banking and trade finance, blockchain ensures clearance of records that cannot be tampered with, resulting in a more trustworthy relationship between the trading partners around the world (Udeh *et al.*, 2024; Ibrahim and Truby, 2021).

4.3. Smart Contracts and Trade Facilitation

In addition to data storage, blockchain can assist in smart contracts that are self-executing contracts that are written in the ledger. They automate the processes of compliance, payments, and logistics and limit the use of intermediaries and the presence of disputes in cross-border trade (Oriekhoe *et al.*, 2024; Lahkani *et al.*, 2020). Blockchain reduces the time of transactions, administrative expenses, and enhances competitiveness by simplifying documentation and allowing it to be verified electronically.

4.4. Integration with AI and IoT

When blockchain is combined with complementary technologies, it increases the transformative potential it has. Location and condition data will be supplied continuously into blockchain networks through IoT devices to increase traceability and provide integrity to all data throughout product lifecycles (Reimers *et al.*, 2019). Blockchain, combined with AI, enables predictive and transparent decision-making, especially in the evaluation of suppliers, ethical sourcing, and fraud detection (Rane *et al.*, 2024; Nwariaku *et al.*, 2024).

4.5. Adoption Challenges

Although it promises something, the adoption of blockchain has serious impediments. The barriers to wide-scale implementation include high implementation and transaction costs, cross-platform interoperability, and uncertainty over scalability (Naseem *et al.*, 2023; Pillai *et al.*, 2022). Integration is also constrained by organizational factors such as process redesign resistance and a lack of technical knowledge (Oriekhoe, Omotoye, Bello, *et al.*, 2024). Additionally, the lack of unification in regulation frameworks makes cross-border adoption in supply chains easier, particularly where the legal status of digital contracts differs.

4. IoT in Supply Chains

IoT is now a fundamental solution to live visibility and responsiveness within the modern supply chains. The IoT solutions bring a sensor and contact to the assets as they capture real-time data on locations, condition, and performance which are the foundations of predictive and adaptive management.

5.1. Real-Time Tracking and Asset Visibility

IoT also strengthens the visibility of the supply chain by allowing constant tracking of goods on their way. The devices are interconnected to monitor location, temperature, humidity, and other measures to keep the distribution of sensitive products like food and pharmaceuticals at quality levels. The real-time visibility eliminates delays, decreases theft and fraud, and enhances responsibility within logistics networks (Arumugam *et al.*, 2018; Junejo *et al.*, 2023).

5.2. Predictive Maintenance and Smart Manufacturing

The IoT in manufacturing helps with predictive maintenance by tracking the health of equipment and notifying about abnormalities prior to equipment breakdown. This will minimize downtime, minimize the cost of maintenance, and increase the life of equipment (Anozie *et al.*, 2024). Quality control systems that use IoT are able to identify defects at any given moment, reducing waste and guaranteeing standards compliance (Ajiga *et al.*, 2024). By assigning IoT to lean manufacturing,

companies can cut the use of resources and enhance responsiveness and agility (Subash *et al.*, 2024).

5.3. Logistics Optimization and Sustainability

IoT supports dynamic route plans and fleet optimisation through a combination of sensor data and analytics to optimise the delivery plan. This lowers fuel usage, reduces the lead times and enhances reliability in the services thus lessening the environmental impact of logistics (Kalinaki *et al.*, 2024). The use of smart sensors also may assist in efficiently managing energy and resources tracking their usage patterns and ascending alterations in them, and ensure the elimination of not only ineffective activities but also sustainable operations of the facility(Subash *et al.*, 2024).

5.4. Data-Driven Decision-Making

The large amounts of data that IoT devices generate present organizations with a chance to take action on, regarding operational performance. Such data may be used to make the real-time decision in procurement, production and distribution on the interference of analytical systems including advanced analytics and integrated into artificial intelligence systems. Indeed, the IoT-based platforms of infrastructure projects, as an example, provide the managers with real-time information on the assets to reduce errors and enhance coordination (Sarkar *et al.*, 2020).

5.5. Challenges and Limitations

Although there are these advantages, there are challenges to the adoption of IoT. Continued problem of interoperability has arisen due to the lack of cohesiveness of the communication standards and thus lack of possibility of network integration. The problem of cybersecurity cannot also be underestimated since the connected equipment opens the additional potential on the malicious attacks (Junejo *et al.*, 2023). In addition, the bulkiness of data generated will demand highly advanced analytics structure and governance schemes that would ensure precision, confidentiality and practicality.

5.6. Sustainable Practices in Supply Chains

Sustainability is a new element of supply chain transformation, triggered by regulatory requirements, stakeholder demands and, the fact that balancing of economic, environmental and social performance is pegged at the long-run competitiveness. Logistics and sourcing sustainability do not just reduce carbon footprints, but also make it more resilient, innovative and trustworthy.

5.7. Green Logistics

Green logistics touches upon the issue of the minimization of the environmental impact of transportation and distribution processes. The strategies to be adopted can be recovering of routes, low-emission cars, alternative fuel source, and collective logistics which significantly reduces carbon emissions and improves efficiency (Muchenje, 2024). Green finance instruments facilitate the transition to carbon neutrality through investments in technologies and infrastructure to support the development of eco-neutral technologies and infrastructure (Zhu *et al.*, 2023). These initiatives are also strengthened by training suppliers on environmental, social, and governance (ESG) standards to align the practices of operations with the sustainability objectives at large (Karaman *et al.*, 2024).

5.8. Circular Economy and Reverse Logistics

The transition of the linear models of take-make-dispose to the circular economy ideas focuses on reuse, recycling and remanufacturing. Circular supply chains recycle the value of end-of-life products, eliminating the need to use virgin resources and eliminating waste (Solomon *et al.*, 2024). The RLS systems allow recovering and reintegrating the material following the IoT and robotics that increase the efficiency of the collection, recycling, and reprocessing processes (Butt *et al.*, 2023; Jayarathna *et al.*, 2023). The circular strategies embedded by firms help them to be more resource-efficient and, at the same time, increase financial and brand reputation.

5.9. Ethical Sourcing

Social responsibility and assurance of transparency in supply chains of various levels is becoming more of a compliance and reputation issue. The blockchain offers incalculable datasets that trace the sourcing behaviour, minimize the risk of exploitation, fraud, or counterfeiting (Nwariaku *et al.*, 2024; Ibrahim *et al.*, 2024). However, sustainable procurement is not a simple matter because of the complexity of global supply chains and inconsistency in applying regulations, as well as the invisibility of small suppliers (Caldera *et al.*, 2022; Ghadge *et al.*, 2021). The solution to these problems entails more formidable regulatory systems, more rigorous auditing policies and more cooperation between stakeholders.

5.10. Global Regulations and Policy Alignment

The international systems that provide recommendations on sustainable management of the supply chain are the Paris Agreement, EU Green Deal and Sustainable Development Goals (SDGs). These are actions that encourage carbon reduction, the application of renewable energy, and green technology inventions (Nguyen and Duong, 2025; Mahmood *et al.*, 2024). Nevertheless, in diverse regulatory settings, MNCs are not good at aligning their strategies between uniformity across the globe and indigenization (Ekemezie and Digitemie, 2024; Srivastava, 2024). Sustainability of corporate governance and the design of standardised reporting practices remains an issue.

5. Integration of Technologies

Digitalization with its transformational capabilities can manifest itself in supply chains not in the individual technologies, but in their complex. Problems are solved by artificial intelligence (AI), block chain, the will of the Internet of Things (IoT), and robotics, and can be combined to create a resilient, transparent and adaptive network that can out-compete siloed answers.

6.1. Synergies Across Technologies

- **AI + IoT:** IoT sensors record operation data (location, condition, and equipment performance) in large volumes that are interpreted using the AI, providing insights into the future. Such a synergy will be able to perform proactive maintenance and active inventory control, real-time logistic optimization (Yuan, 2024; Gheorghe and Soica, 2025).
- **Blockchain + IoT:** IoT can enhance traceability by gathering truly small traces, based on real-time and blockchain can ensure that the data is saved there permanently, where it is not lost and has a high level of security. An integration like this one comes in especially handy within the sector where provenance and quality control are of paramount significance, such as within the realm of farming and food production (Reimers *et al.*, 2019; Kalinaki, 2024).
- **AI + Blockchain**: These two technologies can be used to make proactive decisions as well as have accurate record keeping. One of the first applications of AI to identify anomalies in supplier performance is also selected and blockchain when the suppliers will become transparently verified, which increases the resilience and compliance of the international sourcing (Alzoubi, 2024; Rane *et al.*, 2024).
- **Robotics + AI/IoT:** AI-enhanced warehouse automation, last mile delivery, intralogistics applications: robotics is used with the help of AI algorithms and IoT connectivity. Another advantage of edge computing is the fact that it is more responsive and lowers the latency in time-sensitive updates (Singh and Singh, 2024; Hussain *et al.*, 2024).

6.2. Benefits of Integration

Integrated systems build self-adaptive supply chains that are continuously capable of watching, anticipating and responding to disruption. The combination of transparency, traceability, and predictive intelligence will not only help firms be efficient but more agile and sustainable (Ellururu and Rajalaksmi, 2024). Besides, integration reduces recurrence instances and introduces multifunctional views that would be inaccessible with the individual technologies.

6.3. Interoperability and Standardization Challenges

Although it has its benefits, integration encounters great obstacles. The various platforms have varying data protocols, and thus interoperability has always been a limiting factor (Ademola et al., 2024; Pillai et al., 2022). The use of blockchain systems is an exceptionally challenging topic because security assumptions and consensus mechanism differ across networks, making cross-platform applications hard. Also, the modernization of legacy systems with new digital platforms can be very expensive in terms of redesign and specialized skills. In addition to technical obstacles, the absence of global standards is an additional limitation on the scalability of integrated solutions between industries and regions.

Table 1: Applications of AI, Blockchain, and IoT Across Supply Chain Stages with Sustainability Linkages

Supply Chain Stage	AI Contribution	Blockchain Contribution	IoT Contribution	Sustainability Impact
Procurement	Predictive analytics for supplier selection; risk assessment of geopolitical/economic factors	Smart contracts enforcing compliance and ethical sourcing	IoT-enabled monitoring of supplier operations and certifications	Promotes transparency, fair trade, and responsible sourcing
Production	Predictive maintenance; automated quality control; process optimization	Immutable recording of inputs and production processes for traceability	Smart sensors for monitoring resource and energy consumption	Reduces waste, enhances eco-efficiency, supports circular economy
Logistics & Distribution	Route optimization; demand-driven inventory allocation; disruption forecasting	Tamper-proof tracking of shipments and digital trade finance	Real-time shipment visibility (location, temperature, conditions)	Green logistics through lower fuel consumption and CO_2 emissions
Reverse Logistics	Forecasting and optimizing return flows; AI-driven sorting of recovered products	Traceability of recycled materials; certification of reuse/remanufacture	IoT-enabled tracking of product returns and recycling streams	Supports circular economy, recycling, and closed-loop systems

6. Case Studies

The combination of AI, blockchain, IoT, and sustainability practices does not remain the work of imagination to satisfy, but it already transforms the supply chains in every kind of industries. The case studies that illustrate how these technologies contribute to the collective effort to make an organization efficient, transient and environmental are more than a few.

7.1. ABISChain: AI-Enhanced Blockchain for IoT-Based Supply Chains

ABISChain platform shows how the latency and scaling issues and data consistency of the IoT-activated supply chain can be resolved by AI and blockchain. The Belief Desire Intention (BDI) agents and the algorithm to optimize them will assist ABISChain in increasing the real-time performance of data management by ensuring enhanced security and traceability (Abdelhamid *et al.*, 2024). This demonstration underlines that it is permissible to rely on combined platforms as a measure to address

the inevitability of the technical hurdles that can very easily prevent implementation of the IoT in a scale.

7.2. Wine Industry: Digital Integration for Quality and Transparency

The IoT sensors in the field of viticulture and wine production are used in monitoring the conditions in the vineyard, predicting the quality results, and tracking records with blockchain to make sure of authenticity across the supply chain. This integration will increase the quality of the product as well as the transparency and management of the ecosystem between the producers, distributors, and retailers (Adamashvili *et al.*, 2024). The case indicates the significance of technological convergence in the industries where consumer confidence and integrity of products are the priority.

7.3. Pakistani Retail: Blockchain-Enabled IoT for Sustainable Performance

The examination of the retail sector in Pakistan can demonstrate that blockchain enables the IoT potential to manage the suppliers, internal, and customer reunion that helps to strengthen the logistics performance of the sector and reduce its negative ecosystem effect (Nazir and Fan, 2024). This example case illustrates that integrated technologies can deliver value that is economical and ecological even in resource-constrained settings through the application of data-based efficiency to deliver sustainability outcomes.

7.4. Smart Agriculture: Blockchain and IoT for Sustainable Farming

Integration could be tested well through agriculture and with the transparency of blockchain, real-time crop monitoring offered by IoTs, and data-driven decision-making using AI, agriculture is a perfect place. Lasting as it is, the collaboration of such technologies enhances productivity, which also offers the possibility to utilize resources in a sustainable way and address both ethical sourcing and food safety expectations (Wang *et al.*, 2025). This demonstrates how converged technology can be involved in the bi-fold performance of supply chain effectiveness as well as broader sustainability imperatives in an industry with critically sensitive environmental needs.

7.5. Cross-Sector Evidence

The presence of systematic reviews in blockchain and IoT application to sustainable supply chains can confirm the theory that integration is more effective than using single technology in the application. There are advantages such as an increase in traceability, a decrease in carbon emissions, and an increase in collaboration with stakeholders, demonstrating how a digital convergence helps speed up the transition to the model of a circular economy (Dutta *et al.*, 2022).

7. Barriers to Transformation

The large-scale adoption of AI, blockchain, IoT, and sustainability practices in supply chains is constrained by multiple barriers, Despite promising outcomes. These challenges are economic, technical, organizational, and societal dimensions, often reinforcing one another and slowing the pace of transformation.

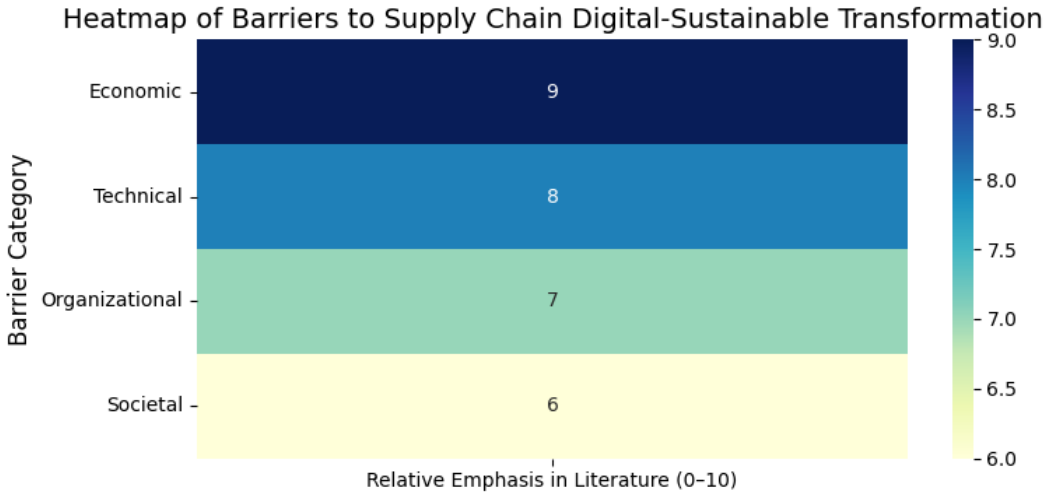


Figure II: Barriers to Supply Chain Digital-Sustainable Transformation.

The figure compares four categories of barriers: economic, technical, organizational, and societal based on their relative emphasis in the reviewed literature. The scale (0–10) represents the frequency and intensity with which these barriers are reported across studies, with higher scores indicating greater prominence.

8.1. Economic Barriers

The most mentioned barrier is the expensive implementation cost. New technologies require massive initial investment in infrastructure, training, and integration of the systems, and returns on investment (ROI) are not certain (Naseem *et al.*, 2023). Uncertainties in transactions and scalability issues can lead to the inability to determine financial results, which is discouraging to invest funds in the firm (Vafadarnikjoo *et al.*, 2021). The issues are particularly acute among micro, small, and medium-sized enterprises (MSMEs), which frequently may not have the needed financial resources and technological base to implement rapidly developed solutions in the supply chains (Karakas *et al.*, 2021).

8.2. Technical Barriers

The technical issues are interoperability, cybersecurity vulnerabilities and data quality. The failure to provide consistent standards of communication across the platform will impede integration, causing inefficiencies and increasing the cost (Oriekhoe, Omotoye, Bello, *et al.*, 2024). With the spread of digitalization, supply chains also get more exposed to cyber threats like ransomware, phishing, and data breaches that can disrupt its processes and affect sensitive information (Melnyk *et al.*, 2021; Odimarha *et al.*, 2024). Moreover, the quality of AI and IoT systems is strongly determined by high-quality and accurate data, and inadequate quality fragmented or inconsistent data is a common challenge faced by most organizations (Toromade *et al.*, 2024).

8.3. Organizational Barriers

Existing practices and a corporate culture can create hindrances in utilizing the new technologies, particularly in those situations when the management is unenthusiastic about digital transformation (Singh and Maheswaran, 2023). There are also managerial hurdles when it comes to connecting the sustainability goals to the business that can quite often result in fragmented or even token attempts rather than the deep-seat change (Baig *et al.*, 2020). The skills are another roadblock to adoption since companies lack personnel trained in data analytics, cybersecurity, and sustainability of the supply chain (Govardhan *et al.*, 2025).

8.4. Societal Barriers

Change raises wider issues in the society. The issue with Labor displacement is also severe since automation and robotics reduce the existence of low- and middle-skilled jobs, bringing uncertainties to the employment and inequality (Anaba *et al.*, 2024; Mohan Banur *et al.*, 2024). With no active reskilling strategy and shift of the labor force, using technology will not diminish social deadlines. In addition, the lack of parity in resource allocation and regulation capacity between the developed and the developing economies further enhances the difference between the two economies, offering asymmetry in the up taking of resources and technology progress.

8. Future Trends

With regards to technologies and the shifting schemes of global governance, the emerging technologies and emerging global governance patterns will define the subsequent wave of supply chain transformation. It is hoped that they will combine to increase the transition to autonomous, transparent, and sustainable networks.

9.1. AI-Driven Autonomous Supply Chains

Machine learning, generative artificial intelligence, and predictive analytics are paving the way to autonomic supply chains with the ability to forecast disruptions, autoregulate logistics, and react to inventory in real time (Rane *et al.*, 2024; Yandrapalli, 2023). The information of the IoT devices, the external market signals and the geopolitical signals, are merged in these systems to enable dynamic decisions requiring little human input. Despite the responsiveness and effectiveness of these inventions, they question the privacy of information, its responsible stewardship, and whether they have become so compliant with the algorithms to entrust them decision-making authority (Eyo-Udo, 2024).

9.2. Digital Twins and Simulation Technologies

Virtual copies of physical objects and processes, digital twins, will be used to promote real-time monitoring, testing scenarios, and predictive planning. Digital twins can assist companies in assessing alternative solutions and enhancing their resilience by facilitating the simulation of supply chain failures (Islam *et al.*, 2025). They are likely to increase their adoption as industries pursue increased agility to react to turbulent global environments.

9.3. Quantum Computing and Advanced Analytics

Quantum computing has the potential to transform the fundamentals of optimization of logistics, routing, as well as resource allocation into complex issues. Although it remains in an experimental phase, its use in the future can significantly decrease the computational bottlenecks and bring breakthroughs in terms of efficiency inaccessible to classical computing (Anaba *et al.*, 2024).

9.4. Web3 and Decentralized Systems

Supply chain governance can also be re-organised through the development of Web3 and decentralized applications that allow peer-to-peer relations to be established without traditional bottlenecks. Blockchain-driven smart contracts could become the core of the procurement, trade finance, and logistics verification, introducing transparency and reducing utilisation of the former mediators (Dong *et al.*, 2024).

9.5. Industry 5.0 and Human–Technology Collaboration

Industry 5.0 prioritizes more the technological cooperation with people when compared to Industry 4.0 which paid more attention to automation and digitization. This trend is likely to be presented in the form of joint robotics, human-oriented AI and sustainability-focused supply-chain design that does not only develop efficient networks, but also social responsibilities (Wang *et al.*, 2022).

9.6. Global Policy and Regulatory Alignment

The extent of the coordination of global policies will dictate how well the overall technology will be adopted. This must have international collaboration to face the geopolitical tension risks, climate change risks, and cyber threats. Heavy reliance on a unified method of gathering data, blockchain certification and sustainability reporting will become invaluable as the solution to cross-border interoperability (Nnaji *et al.*, 2024; Rasshyvalov *et al.*, 2024). At the same time, the disparities need to be addressed with measures that can foster capacity-building in the developing economy, thus that digital-sustainable

supply chains become one of the factors in global inequality (Okoye *et al.*, 2024).

9. Discussion

The examination of AI and blockchain and IoT and sustainability practices reveals that all technologies play the unique roles in transforming supply chains but their value is aligned in inclusion in the mechanism of applying the technologies. The crucial comparison in this section will be made in their roles, and the cross-cutting themes will be identified as well as the gaps in the research which should be filled in order to move on with the scholarship and practice.

10.1 Comparative Insights Across Technologies

In the domain of forecasting, logistics, and risk control, AI demands to offer predictive intelligence so that firms can actively respond to turbulent markets (Nweje and Taiwo, 2025; Abhulimen and Ejike, 2024). These functions are supplemented at every stage of supply chain by the blockchain with its transparency, neutrality, and the feeling of trust, stopping fraud and ensuring compliance (Baranidharan *et al.*, 2025; Kokogho *et al.*, 2025). IoT enhances visibility by incorporating real time monitoring, both in terms of assets and operations, and enhancing traceability and rendering predictive maintenance feasible (Junejo *et al.*, 2023; Anozie *et al.*, 2024). Sustainability practices that anchor the digital transformation to the bigger ecological and social requirements, and supply chains have to fit into the global frameworks, including '- the Paris Agreement and the SDGs (Karaman *et al.*, 2024; Solomon *et al.*, 2024). A combination of these factors creates an ecosystem based on complementary consequences: AI can improve decision-making, IoT can provide live data, blockchain can guarantee the integrity of information, and sustainability can guarantee compliance with environmental and social objectives.

10.2. Convergence and Integration

In the literature, it has been stressed that combined implementations of digital technologies are better than single implementations. As an example, blockchain and IoT are used together to improve traceability and authenticity in agricultural and food supply chains (Adewusi *et al.*, 2023; Reimers *et al.*, 2019), and AI combined with blockchain is used to strengthen predictive analytics with transparent verification (Rane *et al.*, 2024). Systematic reviews also support the argument that blockchain and IoT combined will enhance the sustainable supply chain through a decrease of emissions and efficiency of resources (Dutta *et al.*, 2022; Nwairiaku *et al.*, 2024). Nonetheless, the interoperability issues, risks related to cybersecurity, and high costs remain limiting integration at scale (Pillai *et al.*, 2022; Oriekhoe, Omotoye, Bello, *et al.*, 2024).

10.3. Gaps in Current Research

Nevertheless, gaps still exist despite the huge progress. One, research is more prone to focusing on environmental sustainability (e.g., carbon reduction, green logistics) and less on social sustainability (i.e., labor rights, reskilling, equity in digital adoption) (Khan *et al.*, 2021; Singh and Maheswaran, 2023). Second, most of the research is carried out in technologically advanced economies, and less information is provided on the adoption issues in developing settings, where the infrastructure and the regulatory framework is less developed (Nazir and Fan, 2024). Third, although interoperability is often cited as one of the obstacles, there are not many publications that present scalable, cross-industry solutions to overcome it (Ademola *et al.*, 2024; Bousdekis and Mentzas, 2021). Fourth, even though the usefulness of AI in the domain of forecasting and logistics is well-established, less research critically evaluates its ethical aspects, which include algorithmic bias and responsibility in autonomous decision-making (Sodiya *et al.*, 2024). Lastly, the literature on the long-term ROI of integrated adoption is not well developed, and firms find it challenging to calculate cost-benefit trade-offs (Naseem *et al.*, 2023).

10.4. Toward a Future Research Agenda

These gaps need a multidisciplinary research agenda. Greater attention is to be paid to the social sustainability aspects, such as reskilling of workforce and inclusive digital adoption (Mohan Banur *et al.*, 2024). The interoperability standards of integrating AI, IoT, and blockchain in industries should also be

the subject of research development (Pillai *et al.*, 2022). Inter-regional comparative studies particularly in emerging markets are required in order to find out the context-related enablers/barriers (Nazir and Fan, 2024). In addition, autonomous AI-driven supply chains have to have mechanisms of control to address the ethical and responsibility aspects (Eyo-Udo, 2024). Finally, longitudinal case studies arguably can provide stronger reasons of financial and environmental returns of integrated adoption that firms can embrace to justify the investments (Sanchez Suarez and Sangroni Laguardia, 2023).

10. Conclusion

The world supply chains have found themselves in a momentum step where they confront the waters of geopolitical uncertainty, climate change, and a shifting society that seeks resilience, transparency and sustainability. It has been revealed in the review that this transformation is inspired by artificial intelligence, blockchain and the Internet of Things with sustainability practices as its complements. Despite the different functionality provided by the two technologies, their combination to provide an integrative capability has the greatest impact; predictive intelligence, real-time visibility and immutable traceability provide the capability to build agile and responsive supply networks, which are likely to be accountable.

Case experience has identified less efficiency and reduced risks as additional outcomes of integrated adoption that also encourage larger ecological and ethical goals. However, some economic and technical, organizational and societal hurdles to mass use still exist. A set of such actions as the incentive in form of money, an interoperability infrastructure, commitment of a leadership, and a diverse workforce can be discussed as the only ways to address these problems.

The new trends, such as autonomous supply chains, digital twins, quantum computing, Web3, and Industry 5.0 will change the future of supply chains in the future. However, one has to not only be technologically innovative. The global supply chain has to more and lean towards harmonized governance, ethical governance and global conformity of the policies to deliver equitable and sustainable changes.

Altogether, the digital technologies and the sustainability requirements intersected are not only an upgrade of the operations, but a paradigm shift. But by adopting holistic integration it will be possible to provide efficiency in short term periods to much deeper dive into resilient, transparent, sustainable supply chains able to withstand disruption, and provide benefit in long term to global development.

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