



International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

Advanced Digital Technologies for Enhancing Supply Chain Management

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ABSTRACT

IoT, blockchain, and AI—key Industry 4.0 technologies—are transforming supply chain management. IoT enables real-time tracking and monitoring through sensor-based data, enhancing visibility and responsiveness. Blockchain ensures transparency, traceability, and trust by providing secure, immutable records and enabling smart contracts. AI enhances decision-making through predictive analytics, automation, and risk detection. Combined, these technologies improve operational efficiency, reduce costs, optimize inventory, and strengthen sustainability and resilience. Their adoption requires robust infrastructure, cross-functional collaboration, and strategic alignment. Despite implementation challenges, these technologies are powerful enablers of agile, intelligent, and sustainable supply chains. In this paper, we review the existing research works which study the impacts and issues of applying the advanced digital technologies in supply chain performance measurement.

Keywords: IoT, blockchain, AI, supply chain management

Introduction

In recent years, supply chain management (SCM) has undergone a profound transformation driven by rapid advancements in digital technologies. Among these, the Internet of Things (IoT), blockchain, and artificial intelligence (AI) have emerged as key enablers of innovation. The convergence of these technologies is not coincidental, but rather a response to increasing global complexity, heightened consumer expectations, and the demand for transparency, efficiency, and resilience across supply chains.

Traditionally, supply chains were characterized by fragmented systems, siloed data, manual processes, and limited visibility. These limitations made it difficult for companies to respond quickly to disruptions, forecast demand accurately, or ensure traceability of goods. Globalization and the rise of e-commerce only exacerbated these challenges, requiring supply chains to become faster, more flexible, and more customer-centric.

The need for real-time visibility and data-driven decision-making set the stage for the integration of IoT technologies. IoT devices such as sensors, RFID tags, and GPS systems began to be used for tracking goods, monitoring environmental conditions, and collecting real-time data throughout the supply chain. This allowed companies to improve inventory management, reduce losses, and respond proactively to operational anomalies.

Simultaneously, blockchain technology emerged as a solution to trust, transparency, and traceability issues. In industries such as agriculture, pharmaceuticals, and luxury goods, verifying the origin and integrity of products became increasingly critical. Blockchain's decentralized ledger system allowed supply chain participants to securely share immutable data, reducing fraud, enabling regulatory compliance, and streamlining documentation processes. Smart contracts further enabled automatic execution of agreements, minimizing reliance on intermediaries and reducing delays.

As data volume grew exponentially, the need for intelligent analysis led to the adoption of AI and machine learning. AI enabled predictive analytics for demand forecasting, optimized routing in logistics, automated anomaly detection, and prescriptive decision-making. Natural language processing (NLP) supported customer interaction and document analysis, while computer vision was used for quality inspection and automation in warehouses.

Several external factors accelerated this technological shift. The COVID-19 pandemic, for instance, exposed vulnerabilities in global supply chains, highlighting the need for real-time monitoring, agile planning, and end-to-end visibility. Climate concerns and regulatory pressures also pushed companies toward more transparent and sustainable practices, which these technologies directly support. Moreover, the ongoing development of 5G networks, cloud computing, and edge computing has further facilitated the deployment of these technologies, enabling faster data transmission, decentralized processing, and scalable integration.

In essence, the integration of IoT, blockchain, and AI into SCM was driven by the limitations of traditional systems and the demand for smarter, more resilient, and more transparent operations. These technologies collectively enable supply chains to evolve from reactive systems into intelligent, predictive, and autonomous networks capable of adapting to dynamic market conditions and disruptions. As such, they are no longer optional innovations but strategic imperatives for future-ready supply chains.

The following sections examine the existing studies regarding how the advanced digital technologies can enhance supply chain management. The final section concludes this paper with a few key observations.

IoT

IoT utilizes devices such as sensors, RFID, and GPS to collect real-time data, which is then analyzed to enable real-time tracking of product locations, condition monitoring, and environmental sensing. This contributes to improving visibility, efficiency, and responsiveness across the entire supply chain. Typically, IoT systems are composed of several layers, including data collection, transmission, service, and user interface layers, each of which incorporates various technologies such as sensors, communication networks, middleware, and application software.

Key applications of IoT include inventory management, asset tracking, cold chain monitoring, predictive maintenance, route optimization, enhanced supply chain visibility, waste reduction, and improved sustainability. IoT-based inventory management enables tracking of real-time location, condition, and movement paths of inventory, helping to prevent stockouts or overstocking, improve order fulfillment rates, and facilitate demand planning based on forecasting. In asset tracking, GPS and RFID are used to monitor the real-time location and condition of vehicles, equipment, and high-value assets. In cold chains, environmental data such as temperature and humidity is collected in real time, and alerts are triggered when abnormalities occur, helping to maintain product quality. Additionally, predictive maintenance capabilities allow IoT to monitor the condition of equipment, anticipate failures, and optimize maintenance schedules, thereby reducing downtime and maintenance costs. The large volumes of data collected throughout the supply chain via IoT can also be used in big data analytics to improve supply chain management. Big data analytics enables the construction of predictive models and supports strategic decision-making in areas such as supplier selection, inventory optimization, and demand forecasting.

IoT-based supply chain management can be applied across a variety of industries. For example, in fresh produce supply chains, temperature and humidity monitoring helps maintain product quality; in the pharmaceutical industry, product tracking supports counterfeit prevention; and in the apparel manufacturing sector, RFID enhances transparency in production processes. In most industries, IoT can be effectively used in logistics areas such as warehouse management. Logistics companies are actively adopting IoT technologies to optimize operations, particularly for real-time monitoring and automation of warehouse and logistics processes. Major logistics centers are equipped with RFID tags, sensors, and narrowband IoT (NB-IoT) technology to automate tasks such as inventory location tracking, cargo condition monitoring, and equipment availability checks. The core of IoT-based warehouse automation systems lies in real-time data collection and analysis. Each item in a warehouse is equipped with an RFID tag connected to IoT sensors, enabling automatic tracking of its location, movement path, and stock status. Workers can access this information in real time via mobile devices, thereby eliminating the need for manual scanning and significantly reducing the time required for inventory searches and order picking.

NB-IoT technology can also be used to connect manufacturing lines with logistics systems. Sensors installed on cargo loading platforms continuously monitor platform availability and condition, allowing operators to be efficiently assigned and minimizing bottlenecks and lead times. This improves productivity while reducing unnecessary waiting times and vehicle turnaround delays. IoT can also be used in predictive maintenance systems. For example, sensors attached to conveyor belts and lift equipment in automated warehouses collect data such as vibration, temperature, and operating time. When anomalies are detected, the system automatically sends maintenance alerts, helping to prevent equipment failures and reduce operational downtime.

IoT systems not only improve operational efficiency but also enhance customer satisfaction, operational stability, and environmental sustainability. Real-time inventory management increases order accuracy and reduces shipping errors, while optimized picking routes reduce energy consumption and contribute to lower carbon emissions. These examples demonstrate how IoT can deliver tangible benefits in supply chain quality control, efficiency improvement, cost reduction, and building customer trust across multiple industries.

However, the adoption of IoT comes with several challenges. Issues include data security and privacy concerns, device interoperability, scalability, high initial investment costs, complexity in data management and analytics, organizational change management, shortage of skilled personnel, and regulatory/legal compliance. To overcome these challenges, best practices such as strategic planning, requirements analysis, data governance, technology and vendor selection, pilot projects, cross-departmental collaboration, employee training, and change management must be implemented.

Importantly, IoT can greatly contribute to enhancing the sustainability of supply chain operations. It enables real-time monitoring of resource usage to reduce energy and material waste, optimizes transportation to lower carbon emissions, and allows for full lifecycle tracking of products and materials to support responsible disposal and recycling. Beyond this, IoT offers multidimensional benefits, including improved customer satisfaction, strengthened regulatory compliance, competitive advantage, and enhanced adaptability to future changes.

IoT is an innovative tool that can make supply chain management more efficient, agile, and transparent. It is not merely an automation technology but a strategic enabler of digital transformation in supply chain management. To maximize its effectiveness, a comprehensive approach must be taken—not only ensuring technological readiness but also integrating sensor-based data collection systems, real-time analytics platforms, and strategic decision-making frameworks. This requires alignment across organizational culture, human capabilities, and change management efforts.

Blockchain

The key functions of blockchain for supply chain management can be summarized as follows. First, it offers mechanisms for incentive design and tokenization to promote eco-friendly behavior among consumers. Blockchain enhances product visibility throughout its entire lifecycle, enabling

traceability and carbon footprint analysis. It also improves system efficiency and reduces development and operational costs. Additionally, it facilitates the monitoring and reporting of corporate sustainability performance.

In particular, blockchain's distributed ledger technology can contribute to building trust-based supply chains by increasing transaction transparency and minimizing the role of intermediaries. For instance, through the use of smart contracts, information sharing and transaction terms among supply chain participants can be executed automatically, making it possible to track processes such as recycling and reverse logistics. In practice, some companies have launched blockchain projects across various fields such as food traceability, energy trading, and rewards for green consumption. In the food industry, consumers can trace the origin and distribution history of products via QR codes, thereby improving trust and quality. In the healthcare sector, patients can directly access their medical records, increasing the speed and accuracy of information delivery. In financial trade, blockchain replaces paper-based documents, reducing transaction time and administrative costs. In the automotive industry, blockchain helps prevent fraud such as odometer tampering and ensures transparent vehicle history tracking. In manufacturing, it significantly reduces order approval and production processing times, while enhancing supply chain visibility and error prevention. These examples collectively demonstrate that shared immutable ledgers and smart contracts—the core technologies of blockchain—have a positive impact on supply chain performance. Notable improvements are observed in process transparency, real-time information sharing, automation, error reduction, and operational speed. Moreover, indirect activities such as process mapping, digitalization, and data analysis conducted during blockchain adoption have also contributed to performance improvements.

Agriculture is one of the representative industries where blockchain can revolutionize supply chain operations. Traditionally complex and opaque agricultural supply chains can be dramatically improved through blockchain-based digital platforms. These platforms connect farmers, distributors, buyers, and financial institutions in real time, enabling the entire process of agricultural transactions—including production, storage, transportation, sales, and payments—to be digitally recorded and managed. A key feature of this system is that all transaction records and logistics flows are securely and immutably stored on the blockchain. This allows participants to clearly track roles and responsibilities, minimizing misunderstandings and disputes. For example, data such as harvest time, transportation routes, storage temperature and duration, and final delivery times are automatically recorded, enhancing transparency and traceability. Farmers can sell their harvested crops and receive payments instantly through blockchain-enabled smart contracts, completing transactions more quickly and securely than with traditional systems. While it used to take days or weeks to receive payments after a sale, smart contracts now allow for immediate settlement, improving farmers' cash flow and reducing financial uncertainty. From the consumer's perspective, the system provides a transparent way to verify production history and organic certification. By scanning a QR code on the product, consumers can directly view where and when it was harvested and how it was distributed. This increases confidence in food safety and ethical sourcing. Blockchain helps ensure transactional reliability, reduce reliance on intermediaries, and facilitate direct, trust-based distribution between farmers and consumers.

Blockchain can also enhance supply chain performance when combined with existing technologies. For example, in the retail industry, its decentralized distributed ledger technology helps improve operational efficiency by ensuring the transparency and security of transaction records and preventing data tampering. Real-time transaction verification and data sharing accelerate product delivery and improve customer satisfaction. Smart inventory systems, which feature real-time tracking, demand forecasting, and automated inventory control, help prevent stockouts or overstocking, ensure timely supply, and reduce operational costs. When integrated with blockchain, the effectiveness of such systems is maximized. The combined adoption of blockchain and smart inventory systems in retail is an effective way to enhance supply chain performance, especially when aligned with quality-driven management strategies.

With these features, blockchain can be viewed as a dynamic organizational capability. It reconfigures supply chain resources and competencies, thereby positively influencing performance. Blockchain directly facilitates supply chain integration, which in turn acts as a mediating variable in improving supply chain performance. Supply chain integration is comprised of three dimensions: internal integration, supplier integration, and customer integration. Blockchain supports all three by ensuring the transparency, reliability, and security of transactions, while enhancing collaboration across the supply chain through smart contracts and real-time data sharing. As a result, organizations can achieve better product traceability, quality control, cost reduction, and inventory optimization.

Beyond its technological merits, blockchain fosters inter-organizational trust, ensures information symmetry, and enhances transparency throughout the supply chain. It is especially effective in industries with complex global supply chains, such as automotive, where it supports product traceability, counterfeit prevention, intelligent vehicle communication, and transparent used vehicle transactions. Ultimately, the adoption of blockchain strengthens supply chain integration and serves as a strategic tool to improve sustainable supply chain performance.

On the other hand, blockchain faces several practical challenges, including high energy consumption, scalability limitations, lack of regulatory frameworks, and the rigidity of smart contracts. As a controlling technology, blockchain may lead to increased surveillance, decreased flexibility, and workforce deskilling. Excessive transparency can raise concerns about social monitoring and supply chain fragmentation. Smart contracts, being inflexible by design, may not adapt well to changes, and automation can diminish the roles of middle managers and skilled professionals. Poorly designed incentives could even induce overconsumption, triggering adverse outcomes.

While blockchain presents new opportunities for sustainable supply chain management, it must be implemented not just as a technological tool but as part of a strategically designed and socially responsible framework. True sustainability effects can only be realized when blockchain's core capabilities are combined with organizational readiness, digital transformation initiatives, and comprehensive process redesign.

AI

AI technologies play various roles across the supply chain, including improving forecasting accuracy, supporting decision-making, enabling automation, detecting anomalies, running simulations, and optimizing operations. These capabilities contribute to measurable performance improvements such as cost reduction, shorter lead times, increased productivity, and enhanced customer satisfaction. For example, machine learning is applied to demand forecasting and inventory optimization, while NLP is used for analyzing customer orders, operating chatbots, and reviewing supplier documents. Additionally, AI analyzes real-time data to detect bottlenecks early and is used for scenario analysis to proactively mitigate supply chain risks. The adoption of AI enables learning, prediction, and automated decision-making throughout the supply chain, thereby enhancing production planning, process monitoring, and real-time responsiveness. This transforms supply chains from rigid, hierarchical structures into adaptive systems with greater flexibility, agility, and customization. Such approaches allow for continuous learning and improvement at each component of the supply chain, enhancing both resilience and sustainability.

A representative example of applying AI in supply chain management is using machine learning models to predict product quality inspection results. These models are typically employed to improve productivity and quality and to proactively detect risks within the supply chain. To train such models, various manufacturing-related data must be collected, including product type, production volume, lead time, manufacturing cost, transportation method, and inspection outcomes. AI models analyze the complex relationships among these variables to predict the probability of a product passing quality inspections. Various machine learning models may be used for this purpose, with gradient boosting models being known for minimizing error through the sequential learning of numerous decision trees and effectively capturing nonlinear relationships between variables.

Through data analysis using machine learning, key factors that influence product quality can be identified. For instance, it may be found that products with higher manufacturing costs tend to pass quality inspections more often, or that adjustments in production volume and lead time affect quality outcomes. These models go beyond merely predicting inspection results—they also provide valuable insights for process improvement, resource allocation, and supply chain design. Prediction results can be delivered to managers in real time, enabling proactive actions for high-risk products, rescheduling of production plans, and rerouting logistics, ultimately improving agility and resilience across the supply chain. These examples show that AI technology not only enhances operational efficiency but also contributes to long-term outcomes such as quality assurance and increased customer trust. AI enables preventive thinking in supply chain operations and provides a foundation for strategically balancing quality, cost, and sustainability.

Several categories of factors influence the adoption of AI in supply chain management. Technical factors include the presence of a data-driven culture, maturity of technological infrastructure, and the selection of appropriate algorithms. Organizational factors may involve leadership, internal capabilities, collaboration with external partners, and corporate culture. Environmental factors include market competition, regulatory pressure, and supply chain complexity, while human factors include workforce capability, openness to change, and decision-making skills.

To leverage AI in supply chains, organizations must also meet certain internal requirements. It is essential to establish a culture of data-driven decision-making, ensure the development of technological infrastructure, and build human capital. Cross-functional collaboration and a flexible organizational structure are also crucial. The adoption of AI is not merely an IT issue—it is an enterprise-wide initiative that must be aligned with overall supply chain strategy. Organizations should begin by exploring AI's internal potential and gradually expand its application across the supply chain based on early results. For example, piloting AI in demand forecasting and then expanding it to procurement, production, logistics, and customer service is an effective strategy.

The benefits of adopting AI can be categorized into operational, environmental, social, and economic outcomes. AI improves operational efficiency through inventory optimization, improved demand forecasting accuracy, and personalized customer service. It also supports environmental sustainability by reducing carbon emissions and promoting green logistics. Socially, AI enhances transparency and fairness in supply chains, while economically, it offers benefits such as cost reduction and increased profitability.

Nonetheless, organizations face multiple barriers when adopting AI. Technical barriers include inadequate infrastructure, cybersecurity risks, and insufficient technological maturity. Organizational obstacles may involve lack of executive support, rigid structures, and poor internal communication. Environmental challenges include market uncertainty, regulatory burdens, and industrial dynamics. Economic barriers cover high initial investment costs, expenses related to skilled labor acquisition, and ongoing maintenance. Human barriers include limited understanding, lack of receptiveness to technology, and insufficient training opportunities.

AI can be a powerful tool for enhancing supply chain agility, resilience, and sustainability. However, beyond simply adopting the technology, a balanced approach involving strategic exploration and practical application is essential. Organizations should establish a clear vision and internal alignment strategy from the outset to ensure successful integration of AI into the supply chain.

Conclusions

The integration of IoT, blockchain, and AI technologies represents a transformative shift in supply chain management, redefining how organizations operate, collaborate, and compete in a rapidly changing global environment. Each technology plays a distinct yet complementary role: IoT facilitates real-time data collection and monitoring; blockchain ensures transparency, traceability, and trust; and AI enables intelligent analysis, forecasting, and automation. Together, they form the backbone of a digitally empowered, future-ready supply chain.

IoT enhances supply chain visibility by enabling continuous tracking of inventory, assets, and environmental conditions. It allows organizations to monitor operations in real time, respond quickly to disruptions, and automate routine processes such as inventory counting, cold-chain monitoring, and asset utilization. These capabilities improve operational efficiency and accuracy while reducing labor costs and response time. Blockchain contributes to building trust and accountability across supply chains by offering a decentralized, tamper-proof ledger of transactions. It improves transparency in sourcing, production, and logistics, which is particularly valuable in sectors like agriculture, pharmaceuticals, and manufacturing. Smart contracts further automate compliance and payment execution, reducing reliance on intermediaries and minimizing transaction delays. AI brings intelligence to the supply chain by transforming data into actionable insights in demand forecasting, inventory optimization, production planning, and risk mitigation. It enhances customer experience through personalized services and supports strategic decision-making across procurement, logistics, and service management. When these technologies are integrated, the supply chain becomes not only more efficient but also more agile, resilient, and sustainable. Real-time responsiveness, predictive adaptability, and autonomous decision-making enable organizations to proactively manage uncertainty, reduce environmental impact, and deliver greater value to customers.

However, the adoption of these technologies also presents challenges. Organizations must overcome barriers such as insufficient infrastructure, cybersecurity risks, high implementation costs, and resistance to change. Human factors—such as digital literacy, leadership support, and cross-functional collaboration—play a critical role in successful implementation. Furthermore, ethical considerations, regulatory compliance, and the social implications of automation and data transparency must be carefully managed.

To realize the full potential of IoT, blockchain, and AI in SCM, companies need a holistic strategy. This includes investing in digital infrastructure, building internal capabilities, fostering a data-driven culture, and ensuring alignment with overall business objectives. Pilot projects, scalable implementation plans, and continuous learning are essential to driving sustainable transformation. IoT, blockchain, and AI are not just technological tools; they are strategic enablers of innovation in supply chain management. When thoughtfully implemented, they empower supply chains to become intelligent, customer-centric, and sustainable ecosystems. As global markets grow more volatile and customer expectations rise, embracing these technologies is no longer optional—it is essential for long-term competitiveness and resilience.

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