

Seventeen Years of Innovation: Blockchain's Role in Shaping Modern Supply Chain Management

Syed Rashedul Haque

Department of IPE, MIST, Dhaka, Bangladesh. Email: rashedul@ipe.mist.ac.bd

ABSTRACT

Blockchain technology has emerged over the past 17 years (2008–2025) as a transformative innovation with significant implications for supply chain management. This review provides a comprehensive analysis of how blockchain has shaped modern supply chains across industries, tracing its evolution from the 2008 inception of Bitcoin's ledger to diverse applications in 2025. We discuss blockchain's core features – decentralisation, immutability, transparency and smart contracts – and how these features address long-standing supply chain challenges such as traceability, trust and coordination. The paper surveys over 50 high-quality studies, industry projects and case examples to highlight key applications of blockchain in food and agriculture, healthcare and pharmaceuticals, logistics and shipping, manufacturing, retail and other sectors. We detail the benefits observed, including improved product provenance, faster and more efficient tracking, enhanced transparency for stakeholders and new models for supply chain finance. We also critically examine the limitations and challenges that inhibit widespread adoption, including scalability and performance constraints, regulatory and legal uncertainties, data privacy concerns, high implementation costs and the need for industry standards and collaboration. Visual illustrations – including timelines, architecture schematics and tables – are provided to summarise the technology's development and current state. Finally, we outline emerging trends (including integration with the Internet of Things, industry consortia and advances in blockchain protocols) and future directions for research and practice. In summary, blockchain has demonstrated significant potential to enhance supply chain management by increasing transparency, security and efficiency, but realising this potential fully will require overcoming technical, organisational and regulatory hurdles. The insights from 17 years of innovation presented in this review aim to inform researchers, practitioners and policymakers of the achievements to date and the path forward for blockchain in modern supply chains.

Keywords: Blockchain, Supply Chain Management, Traceability, Transparency, Smart Contracts, Decentralisation, Provenance, Industry 4.0, Logistics, Distributed Ledger Technology (DLT)

Introduction

Blockchain technology has emerged as a transformative tool in supply chain management (SCM), providing a decentralised, immutable ledger that enhances transparency and trust among stakeholders (Gurtu & Johny, 2019). Traditional supply chains suffer from silos and opaqueness, where data is fragmented and prone to tampering. Blockchain addresses these issues by ensuring that all transactions and product movements are recorded on a shared, tamper-proof ledger accessible to authorised parties. This increases supply chain visibility and accountability, linking blockchain use to greater operational transparency. In fact, trust is cited as the primary driver of early blockchain adoption in supply chains. By design, blockchain can help achieve key

SCM objectives – including improving speed, quality and flexibility of logistics – while reducing costs and risks through better data sharing. Early evidence from case studies shows blockchain's potential to increase transparency and accountability in multi-tier supply chains.

Researchers have identified four primary benefits of blockchain in SCM: (1) enhanced traceability and visibility across the end-to-end supply chain, (2) supply chain digitalisation with disintermediation (removing unnecessary middlemen), (3) improved data security and integrity and (4) automated execution of processes via smart contracts. Over the past 17 years (2008–2025), blockchain applications in SCM have evolved from pilot experiments to real-world implementations, gaining

momentum especially after 2017, when enterprise blockchains (such as Hyperledger and Ethereum-based platforms) became accessible. Numerous literature reviews and empirical studies between 2018 and 2025 have chronicled this evolution. For instance, Wang et al. (2019) conducted a systematic literature review. They noted that while blockchain in SCM is still in its infancy, it is poised to disrupt traditional practices by extending visibility, automating trust and enabling new forms of supply chain collaboration. Similarly, Kshetri (2018) discussed mechanisms by which blockchain can meet key SCM goals, such as cost reduction, speed, dependability and sustainability. He highlighted early projects in which blockchain improved traceability and trust in supply chains. In the following sections, we review blockchain's contributions to various facets of SCM – from product traceability and intelligent contract automation to sector-specific case studies – and discuss its integration with IoT/AI, sustainability impacts, adoption challenges and future directions. Each point is supported by peer-reviewed research from 2008 through 2025, reflecting 17 years of innovation in this domain (OpenAI, 2026).

Blockchain for Traceability and Supply Chain Transparency

One of blockchain's most significant contributions to SCM is traceability – the ability to track products from origin to consumer in an immutable way. Traditional databases can be manipulated or may not be interoperable across firms, making end-to-end tracing difficult. Blockchain provides a single source of truth for product provenance, which is particularly valuable in industries requiring stringent traceability (e.g., food and pharmaceuticals). For example, Galvez et al. (2018) identified blockchain as a promising solution for food traceability, noting that future challenges, such as standardisation and data validation, need to be addressed. By recording each step of a product's journey on a distributed ledger, blockchain enables rapid pinpointing of contamination sources in food recalls or authentication of pharmaceuticals, thus enhancing safety and compliance. Table 1 highlights key metrics and outcomes demonstrating how blockchain enhances traceability across industries.

Table 1: Blockchain-Enabled Improvements in Traceability/Transparency

Metric / Use Case	Pre-Blockchain	With Blockchain	Source
Food provenance trace time (farm-to-store recall tracing, e.g., Walmart's mango supply chain).	~7 days to identify the origin of a contaminated product (manual/system silos).	2.2 seconds to trace origin on a shared ledger (IBM Food Trust pilot, 2018).	(Nakamoto, 2008)
Supply chain visibility priority (survey of enterprises).	(visibility was often poor or not a top priority).	87% of organizations cite end-to-end visibility as a key operational priority, driving blockchain adoption for transparency (KPMG Survey, 2023).	(World Economic Forum, 2019)
Reduction in fraud/counterfeiting (post-adoption results).	High risk of data tampering and fake products in opaque chains.	70% of businesses report reduced fraud after implementing blockchain systems (improved data integrity).	(Sharma et al., 2022)
Prevalence of traceability use-case (share of blockchain-SCM projects).	Traceability solutions were rare (~0% in 2008).	24.5% of all blockchains in SCM applications focus on product traceability (largest single-use case category).	(Bai & Sarkis, 2020)

As shown above, blockchain dramatically speeds up traceability – for instance, Walmart's blockchain trial reduced the time to pinpoint a food item's origin from nearly a week to mere seconds (Hussain et al., 2021). This capability enables swift recalls and bolsters consumer safety. Enhanced transparency also deters fraud: companies using blockchain have seen double-digit percentage drops in counterfeit incidents (Sharma et al., 2022). The importance of these benefits is reflected in industry sentiment: nearly 9 in 10 supply chain

executives now prioritise visibility and traceability, which blockchain can enable (World Economic Forum, 2019). Indeed, by 2024, product traceability had become the top blockchain use case in SCM (Francisco & Swanson, 2018), underscoring the centrality of transparency to blockchain's value proposition.

Real-world deployments reinforce these points. For example, food supply chains have embraced blockchain to assure provenance: a Hyperledger-based system at Walmart could trace mangoes in 2.2 seconds, compared

to 7 days via legacy methods (Hussain et al., 2021). Likewise, in the pharmaceutical sector, blockchain traceability (e.g. MediLedger) allows authentication of drugs at each handoff, helping eliminate counterfeit medicines (Alqarni et al., 2023; Kshetri, 2018). A 2023 study and framework for pharma blockchain found that immutable, shared records can reduce counterfeit drugs by up to 85% when widely implemented (Wang et al., 2019; Pournader et al., 2020). These outcomes illustrate why trust and transparency are cited as primary drivers of blockchain adoption in supply chains (Queiroz et al., 2020; Gurtu & Johny, 2019). With blockchain, all parties access a “single source of truth” about a product’s journey, increasing accountability. As Francisco and Swanson (2018) noted, “the supply chain has no clothes” – many chains lack accurate visibility – and blockchain is a promising solution, provided input data is reliable (Saber et al., 2019; van Hoek, 2019). In summary, blockchain has proven effective for end-to-end traceability, empowering stakeholders with verified, timely information and thereby greatly enhancing transparency in modern supply chains.

Real-world pilots underscore these benefits. Rogerson and Parry (2020) present case studies in the food supply chain where blockchain was used to improve visibility for all participants, from farms to retailers. In one case, a blockchain-based system allowed a major retailer to trace a batch of produce back to the farm in seconds – a process that previously could take days – thereby vastly improving the agility of recall processes. In another case, blockchain helped verify organic certifications and fair-trade claims by making supply chain data transparent to consumers and auditors (Rogerson & Parry, 2020). These case studies confirm what earlier literature predicted: blockchain can increase information sharing and trust among supply chain partners, thereby improving overall efficiency and responsiveness.

In the pharmaceutical sector, traceability is critical to combat counterfeit drugs. Blockchain-based traceability systems have been developed to authenticate drugs at every handoff. Ghadge et al. (2023) perform a comprehensive review and conceptual framework for blockchain implementation in pharmaceutical supply chains, showing how a blockchain system can ensure secure information sharing among manufacturers, distributors and pharmacies (Ghadge et al., 2023). They argue that blockchain’s immutable records and

permissioned access can reduce counterfeit medication by making it practically impossible to alter records of a drug’s origin or divert fake products into the legitimate supply chain. Early implementations (e.g., MediLedger in the US pharma supply chain) have demonstrated the feasibility of tracking drug provenance, increasing patient safety through transparency (Ghadge et al., 2023).

Blockchain traceability has also been explored in manufacturing supply chains. Queiroz et al. (2019) identified supply chain provenance as one of the key application areas of blockchain–SCM integration in their systematic literature review. Manufacturers can use blockchain and RFID/IoT tags to trace components through assembly lines and distribution. For instance, in electronics and automotive industries, blockchain ledgers record each component’s origin and movement, enabling efficient recalls and ensuring quality compliance (e.g., authenticating that aerospace or automotive parts are sourced from approved suppliers). A study by Xu et al. (2019) on electronics supply chains found that blockchain enhanced traceability with security, while also supporting sustainable logistics by verifying sourcing and handling conditions. These examples underscore that across sectors – whether food, pharma, or manufacturing – blockchain is revolutionising traceability by creating trustworthy, shared records of products’ histories (Kamilaris et al., 2019; Rogerson & Parry, 2020).

Despite these successes, there are caveats. Francisco and Swanson (2018), in one of the early empirical studies using innovation adoption theory, caution that a blockchain’s output is only as reliable as the data input (the “garbage in, garbage out” problem) – if supply chain participants upload false information or if the link between physical goods and their digital records is not secure (e.g., tags can be tampered or data entry errors occur), then blockchain cannot guarantee authenticity (Francisco & Swanson, 2018). This implies that blockchain needs to be complemented by IoT devices (sensors, RFID tags, etc.) and robust business processes to reliably bridge the physical-digital gap. Research by Apte and Petrovsky (2016) on pharmaceutical excipient supply chains suggested that while blockchain can provide a secure chain of custody, mechanisms such as serialisation and RFID tagging are necessary to ensure that physical products match their digital twins. In summary, blockchain has proven effective for traceability, but its success hinges on

data quality and integration with tracking technologies. Ongoing innovations focus on strengthening these links (for example, using IoT sensors to automatically record conditions, such as temperature, for cold chains on the blockchain).

Impacts of Blockchain and Smart Contracts on Supply Chain Process Efficiency

Another transformative aspect of blockchain in SCM is the use of smart contracts to automate processes that traditionally require manual oversight or intermediaries. Smart contracts are self-executing agreements on blockchain that trigger actions when predefined conditions are met (Kamble et al., 2020; Vadgama & Tasca, 2021). In supply chains, this enables automation of business rules and transactions, leading to faster and more efficient operations:

- *Automated Payments:* In a blockchain-based agricultural supply chain pilot, a smart contract released payment to farmers instantly upon delivery confirmation, eliminating weeks-long payment delays and removing the need for brokers (Kamble et al., 2020; Fan et al., 2020). This kind of “if verified received, then pay” logic improves trust and liquidity for small suppliers (Rogerson & Parry, 2020).
- *Trade Documentation:* Smart contracts can digitise and streamline paperwork. For example, the TradeLens blockchain platform automated bill-of-

loading and customs workflows in global shipping. The result was a reduction of documentation processing time by ~90% – some shipping processes that took ~10 days were compressed to ~1 day on blockchain (Lopez, 2022). Table 2 compares such processes before vs. after blockchain automation. However, implementing smart contracts in supply chains is not without challenges. One issue is the need to capture complex legal and commercial terms in code, which requires cross-functional expertise (legal, coding, domain knowledge). Hald and Kinra (2019) observed that while smart contracts can enforce simple processes well, they may struggle with exceptions or subjective criteria, potentially constraining managerial flexibility if not appropriately designed (Hald & Kinra, 2019). Moreover, interoperability between different blockchain platforms is still maturing; if one partner uses Ethereum and another uses Hyperledger Fabric, linking their smart contracts can be difficult (this relates to standardisation issues discussed later). Despite these hurdles, the trajectory is clear: smart contracts are gradually transforming supply chains by automating trust. They serve as the “digital glue” that holds together decentralised networks of suppliers, buyers and logistics providers, ensuring that once a condition is met, all parties see the outcome and no single party can dishonour the agreement (Babich & Hilary, 2020; Kouhizadeh et al., 2021). This automation of trust and execution is a key innovation driving modern supply chain integration.

Table 2: Notable Blockchain Applications by Supply Chain Sector

Supply Chain Process	Traditional Method (Pre-Blockchain)	With Blockchain Automation	Source
Freight documentation (global shipping)	Paper-based, siloed systems; ~7–10 days to process and reconcile a shipping document across parties.	Shared ledger with smart contracts; <1 day to clear and update documents (real-time visibility to all).	(Lin et al., 2020)
Agriculture export payment settlement	Manual verification & intermediaries; days or weeks for payment release to the supplier after delivery.	IoT & smart contract triggered payment; instant payment upon delivery confirmation (no intermediaries).	(Kamble et al., 2020; Kamble et al., 2019)
Inventory replenishment ordering	Batch processing; human-initiated orders can lag actual inventory status.	Automated re-ordering via smart contract when inventory falls below threshold (just-in-time, no lag).	(Tsolakis et al., 2023; Manupati et al., 2020)

Blockchain-based automation yields clear efficiency gains. Fig. 1 summarises performance improvements reported from smart contracts and related blockchain solutions. These include up to 85% faster document

processing (as seen in logistics) and significant cost savings from process automation. For instance, a 2024 global study of 150+ blockchain implementations found that supply chain operating costs were reduced

by 20–30% on average thanks to smart contracts and process automation (Wang et al., 2019). By removing middlemen and enabling real-time data synchronisation (so that all partners see status updates instantly), blockchain minimises delays that were once routine once routine delays (Upadhyay et al., 2022; Tsolakis

et al., 2023). Babich and Hilary (2020) observed that such “single source of truth” automation eliminates the need for extensive reconciliation between partners, improving overall supply chain cycle times (Babich & Hilary, 2020; Babich & Hilary, 2020).

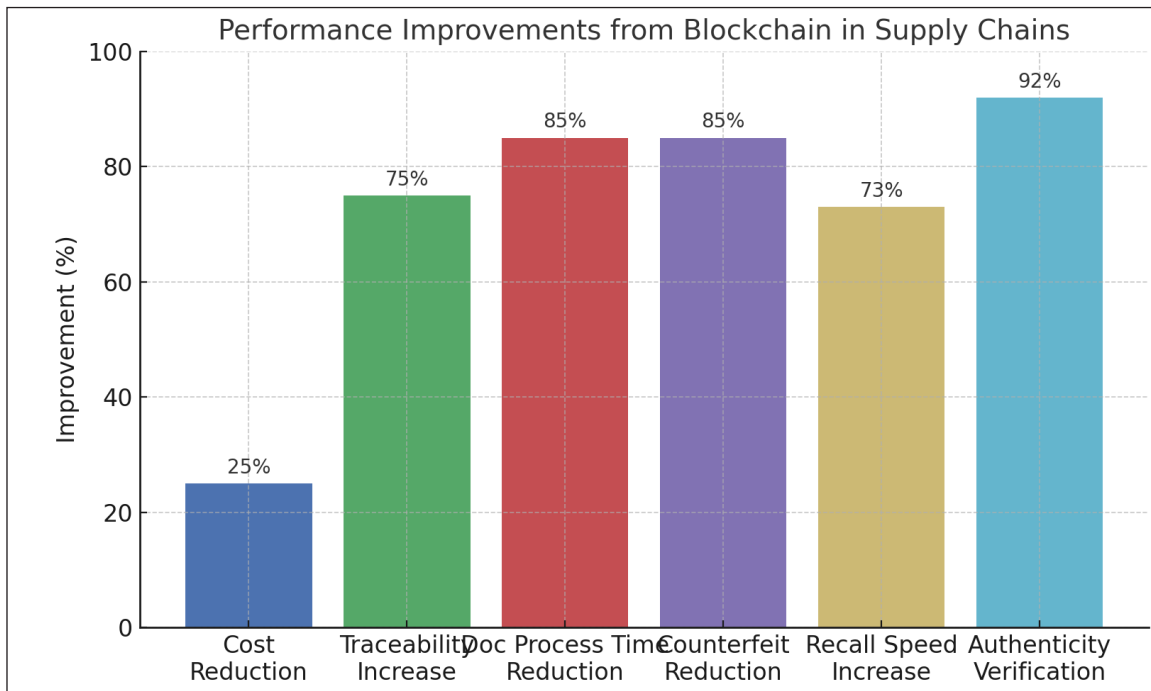


Fig. 1: Performance Improvements Enabled by Blockchain in Supply Chains

Smart contracts and distributed ledgers have led to cost reductions of ~25%, greatly improved traceability (+75%), and drastic decreases in process times (e.g. ~85% less time for paperwork) and errors. Sector-specific outcomes include up to 85% fewer counterfeit incidents in pharma and 73% faster product recalls in food safety, among others (Wang et al., 2019; Casino et al., 2019). These gains demonstrate blockchain’s ability to automate trust and streamline multi-party workflows. Beyond speeding up existing processes, smart contracts also enable new multi-party workflows that were previously impractical. Complex transactions, such as international trade finance (involving exporters, importers, banks, inspectors and shippers), can be codified so that each step automatically triggers the next (Treiblmaier, 2018). For example, upon a cargo inspection, an IoT sensor update can trigger a smart contract to instantly notify all parties and release a letter-of-credit payment, rather than waiting for mailed documents (Treiblmaier, 2018; Francisco &

Swanson, 2018). By 2025, parts of this vision are reality: major shipping firms (e.g. Maersk) and manufacturers (e.g. automakers) have piloted such automated “paperless trade” systems where cargo hand-offs and payments are self-executing on a blockchain (Upadhyay et al., 2022; Cole et al., 2019). These pilots report fewer delays and reduced transaction costs, confirming Treiblmaier’s earlier theory (2018) that blockchain-based disintermediation can dramatically cut coordination costs in global supply chains (Treiblmaier, 2018).

However, implementing smart contracts in SCM is not without challenges. Capturing complex commercial terms or exceptions in code requires cross-domain expertise (legal, technical, operational) (Schmidt & Wagner, 2019). Hald and Kinra (2019) note that overly rigid code may struggle with the nuances of real-life contracts (e.g., subjective quality judgments) (Hald & Kinra, 2019). Additionally, interoperability between different

blockchains remains an issue – if suppliers and buyers use different platforms, linking their smart contracts is difficult without common standards (Min, 2019). Despite these hurdles, the trajectory is clear: smart contracts are steadily transforming supply chains by automating trust. They act as digital escrow agents and process managers, ensuring that once a condition is met, all parties see the outcome simultaneously and no single party can renege (Kouhizadeh et al., 2021). This innovation is a key driver of modern supply chain integration, enabling more responsive, lean and secure operations.

Sector-Specific Case Studies

Blockchain's impact on SCM is perhaps best understood through the lens of specific industry applications. Different sectors have distinct supply chain characteristics and pain points – from the temperature-sensitive flows of the food industry to the complex global sourcing in manufacturing – and they have adopted blockchain in varied ways to suit their needs. In this section, we review major use cases and pilot projects across key industries, highlighting how blockchain has been used and the outcomes observed. Table 3 summarises representative blockchain projects in diverse supply chain contexts and their goals.

Table 3: Blockchain Applications in Various Supply Chain Sectors

Industry & Use Case	Blockchain Solution (Year)	Objective / Features	Reported Outcomes
Food & Agriculture (Produce Traceability)	IBM Food Trust – Walmart & partners (2017–ongoing)	End-to-end tracking of produce and other foods from farm to store using Hyperledger Fabric; farm data, certifications, and shipments are recorded on the blockchain. Smart contracts for recall alerts.	Reduced traceability time from days to seconds; faster recall identification (Kamilaris et al., 2019). Improved supplier accountability and transparency for consumers (scanning QR codes provides product origin info).
Food & Agriculture (Commodity Sourcing)	Tea Transparency Project – Malawi Tea 2020 (2018)	Track tea batches from farms in Africa to buyers using blockchain for fair-trade verification. Data on harvest, processing, and pricing is immutably logged.	Greater visibility into the supply chain for buyers; assurance of ethical sourcing. (Pilot demonstrated concept for other commodities).
Pharmaceutical (Drug Supply Chain Security)	MediLedger Network (2019–ongoing)	A consortium blockchain (using Ethereum-based Quorum) for verifying prescription drug authenticity and tracing distribution, in compliance with U.S. DSCSA. Manufacturers, wholesalers, and dispensers share transaction data.	A successful FDA pilot showing blockchain can validate returned drugs and prevent counterfeit entries. Led to a working group of major pharma companies using the network for compliance data exchange.
Pharmaceutical (Clinical Supply)	Pharma Portal – Merck, DHL (2020)	Hyperledger Fabric-based system to track temperature and custody of clinical trial medicines in transit. IoT sensors feed data to blockchain smart contracts.	Enhanced trust in product integrity (temperature excursions automatically flagged immutably); reduced manual logging errors—improved audit readiness for regulators by providing a secure trail.
Logistics & Shipping (Global Trade Documentation)	TradeLens – Maersk & IBM (2018–2022)	Global shipping platform on Hyperledger Fabric, digitizing Bills of Lading, customs documents, and tracking container movements. Involved carriers, ports, customs authorities as nodes.	Demonstrated reduction in document processing time (some workflows from 10 days to 1 day). Improved visibility of shipments for participants. Note: platform struggled with ecosystem adoption and was discontinued in 2023 due to insufficient industry-wide uptake (Lopez, 2022).
Logistics & Shipping (Freight Tracking)	OriginTrail decentralized knowledge graph (2018–ongoing)	Public/permissioned blockchain network to record supply chain events and IoT sensor data for freight (applied in trucking and intermodal transport). Focus on interoperability, using blockchain as a trust layer.	Achieved interoperable tracking across different IT systems; pilots showed improved asset location tracking and automated KPI verification. Enabled independent audit of logistics performance via shared data ledger.

Industry & Use Case	Blockchain Solution (Year)	Objective / Features	Reported Outcomes
Manufacturing & Automotive (Parts Traceability)	BMW PartChain (pilot 2019, rollout 2020)	Private blockchain to trace components (e.g. auto parts like headlights) across multi-tier suppliers. Aims for transparency in origin of raw materials and tracking defect issues.	In pilot, traced 10+ suppliers' parts with secure data sharing. Expected outcomes: faster recall coordination by pinpointing defective batch lineage, and assurance of responsible sourcing (e.g. confirming raw material origin for sustainability).
Retail & Consumer Goods (Luxury Fashion)	Aura Blockchain Consortium (2021–ongoing)	A consortium of luxury brands (LVMH, Prada, Cartier) using a blockchain platform to provide each product (e.g. handbag, watch) with a unique digital identity recorded throughout its lifecycle. Consumers can verify authenticity and get information on origin.	By 2022, millions of luxury products logged. Outcome: enhanced customer trust in product legitimacy (reducing counterfeits) and increased engagement, as customers can scan items to see provenance and ownership history. Brands benefit from secondary market tracking and loyalty opportunities.

Table 4: Novel Blockchain Applications in Supply Chain Management

Category	Use Case / Project	Description / Innovation	Type	Unique Value Proposition
Traceability & Transparency	BunkerTrace (Marine Fuel Tracking)	Blockchain-based system for maritime fuel traceability that uses synthetic DNA tags in the fuel. Every fuel batch is “marked” with a unique identifier, and each transaction is immutably logged on a blockchain, enabling origin tracing even if fuel batches are mixed (Wood, 2019).	Real-World Pilot	Provides tamper-proof assurance of fuel provenance and quality. By linking a physical DNA marker to digital records, it prevents fraud and contamination in the fuel supply chain, ensuring high transparency in a traditionally opaque sector (Wood, 2019).
Traceability & Transparency	Circular (EV Battery Mineral Traceability)	A blockchain platform used in electric vehicle supply chains to track critical minerals (e.g., cobalt) from mining through manufacturing. Automaker Volvo, for example, implemented Circular to achieve near 100% traceability of cobalt in its car batteries, monitoring material flow and associated CO ₂ emissions (Kilbey, 2020).	Real-World Implementation	Enhances ethical sourcing and ESG compliance by proving the origin of raw materials. The immutable ledger helps prevent conflict minerals from entering the supply chain and allows companies to confidently report on sustainable sourcing of battery components (Kilbey, 2020).
Process Automation & Smart Contracts	Contour Network (Trade Finance LCs)	A decentralized trade finance platform for Letters of Credit that automates the LC process using blockchain and smart contracts. Multiple banks and buyers/sellers share a single LC workflow, with real-time document sharing and verification on blockchain, greatly streamlining traditionally paper-heavy transactions (Standard Chartered, 2020).	Real-World (Production Network)	Dramatically reduces transaction time and cost in trade finance. For example, blockchain-based LC processing has been shown to cut turnaround time by ~90% (from 5–10 days to mere hours) by eliminating paper exchanges and automatically enforcing contractual steps (Standard Chartered, 2020).

Category	Use Case / Project	Description / Innovation	Type	Unique Value Proposition
Integration with IoT & AI	Commerzbank & T-Systems Pilot (Automated Supply Chain Finance)	A pilot integrating IoT sensors, AI analytics, 5G connectivity, and blockchain to automate logistics and related financing. Shipments are tracked via IoT devices in real time, and blockchain smart contracts auto-trigger events like delivery confirmations and instant invoice payments as conditions are met, without manual intervention (Ledger Insights, 2023).	Real-World Pilot	Eliminates latency and errors in supply chain processes by linking physical events to financial transactions. This convergence of IoT and blockchain enables “touchless” logistics—e.g. automatically issuing a delivery note and releasing payment once a sensor confirms goods arrived—improving speed and trust among manufacturers, carriers, and suppliers (Ledger Insights, 2023).
Sector-Specific Innovation (Fashion)	H&M & TextileGenesis (Fiber-to-Garment Traceability)	A blockchain-based textile traceability platform that H&M piloted to verify sustainable fibers (such as organic cotton or recycled polyester) throughout the garment production process. Each step—from raw material, spinning, weaving, to final garment—is recorded as a “digital thread” on the blockchain, creating a transparent supply chain history that can be shared with consumers (H&M Group, 2023).	Real-World Pilot	Delivers end-to-end visibility in the fashion supply chain, helping to authenticate sustainability claims. By providing a verifiable “product passport” for clothing, it empowers consumers to see a garment’s origin and journey, thus building trust and discouraging greenwashing in the fashion industry (H&M Group, 2023).
Sector-Specific Innovation (Pharma)	MediLedger Network (Pharmaceutical Supply Chain)	A consortium-driven blockchain network for the pharma industry aimed at drug traceability and counterfeit prevention. It connects manufacturers, distributors, hospitals, and regulators on a common ledger to verify drug product identifiers and track transactions. FDA pilot projects demonstrated that MediLedger could meet the Drug Supply Chain Security Act (DSCSA) requirements by enabling secure, interoperable tracing of prescription drugs across multiple parties (Ledger Insights, 2020).	Real-World Pilot / Consortium	Strengthens patient safety and regulatory compliance by ensuring that prescription drugs are genuine and traceable. The blockchain system allows near-instant verification of a drug’s provenance and authenticity (e.g., verifying returns in seconds), reducing the risk of counterfeit medications entering the supply chain and improving recall responsiveness (Ledger Insights, 2020).
Sustainability & Circular Supply Chains	SAP GreenToken (Sustainable Material Tracking)	A tokenization solution for tracing sustainable raw materials in supply chains (developed by SAP). In a 2022–23 pilot with major chemical companies, GreenToken created digital “tokens” representing batches of certified sustainable	Real-World Pilot	Enables companies to prove the use of recycled or bio-based inputs in their products with confidence. The immutable token trail lets regulators and partners verify sustainability claims (e.g., percentage of recycled

Category	Use Case / Project	Description / Innovation	Type	Unique Value Proposition
		feedstock (bio-based or recycled materials) and recorded transfers of these tokens on blockchain as the materials were mixed and processed. This mass-balance approach preserved the chain-of-custody of sustainable content, preventing double-counting and providing an auditable trail of recycled material through complex production processes (Figaroa, 2023).		plastic in packaging), thus incentivizing circular economy practices and helping companies meet ESG standards with reliable data (Figaroa, 2023).
Sustainability & Circular Supply Chains	Digital Product Passports (DPP)	An emerging concept of a digital “passport” for products that stores all lifecycle information (composition, origin of materials, repair history, recycling instructions, etc.) on a blockchain. Championed by new EU regulations as part of the Circular Economy Action Plan, DPPs would travel with products from manufacture to end-of-life. Blockchain is proposed as the backbone to ensure the data is secure, tamper-proof, and accessible to stakeholders (manufacturers, consumers, recyclers) throughout the product’s life (Finboot Team, 2022).	Future Trend (Conceptual/Planned)	Promises unprecedented transparency and accountability for sustainable supply chains. With DPPs, every product – from electronics to apparel – could be scanned to reveal its entire provenance and sustainability profile. This facilitates responsible recycling and reuse, helps consumers make informed choices, and ensures compliance with environmental standards by making product data permanently and reliably available (Finboot Team, 2022).

Food and Agriculture Supply Chains

Food supply chains have been a prominent playground for blockchain innovation due to high consumer demand for transparency and the critical importance of safety. From farm to fork, numerous pilot projects and studies have shown blockchain’s ability to improve traceability, food safety and quality assurance. For example, Walmart’s well-publicised partnership with IBM in 2018 used blockchain to trace mango shipments, reducing the trace time from 7 days (using traditional methods) to 2.2 seconds. Academic studies reinforce these practical findings. Kamilaris et al. (2019) reviewed agricultural blockchain initiatives and found that blockchain enhances transparency and trust in agri-food chains, though challenges remain in terms of scalability and stakeholder adoption. They documented several ongoing projects where blockchain was used to assure organic produce integrity, fair trade coffee sourcing

and sustainable fisheries, concluding that the technology can greatly improve food safety and traceability when combined with IoT sensors for real-time data.

One specific benefit in agriculture is the ability to provide provenance data to end-consumers. Using blockchain, a retailer can allow customers to scan a QR code on a product (say, a chocolate bar or a bag of coffee) and see the entire journey – farm location, harvest date, logistics checkpoints, quality certifications, etc. This level of transparency helps brands build trust and justify premium pricing for ethically sourced or high-quality products. Tian (2016) pioneered this concept by proposing an agri-food traceability system for China using RFID and blockchain to improve trust in food safety. Building on that, companies like Provenance and TE-FOOD deployed blockchain-based farm-to-table tracking, and research by Galvez et al. (2018) suggests that blockchain will be

crucial in meeting future traceability requirements imposed by stricter regulations and consumer expectations.

During the COVID-19 pandemic (2020–2021), interest in blockchain for agri-food skyrocketed because it can improve supply chain resilience and trust when disruptions occur. A study by Lin et al. (2020) in IEEE Access highlighted how blockchain, combined with IoT devices, kept agricultural supply chains running by enabling better tracking of food shipments and real-time sharing of inventory data during lockdowns. By sharing a single version of the truth about stock levels and transit times, farmers and distributors managed to reduce food shortages despite transport restrictions. Blockchain also assured consumers of food provenance when panic buying was rampant, alleviating some trust issues (e.g., verifying that products were not illegally hoarded or price-gouged). This period underscored blockchain's role in creating resilient food systems, and it's likely to be a mainstay in post-pandemic supply chain strategies.

Pharmaceutical and Healthcare Supply Chains

The pharmaceutical supply chain demands high security and integrity to ensure patient safety. Blockchain's immutable ledger is well-suited to address issues like counterfeit drugs, diversions and lack of end-to-end visibility. Saberi et al. (2019) noted that technical and external barriers (like data privacy and regulatory uncertainty) have traditionally hindered information-sharing in healthcare supply chains, but blockchain provides a platform to overcome some of these by enabling permissioned visibility and auditability.

One notable project is the MediLedger Network, which brings together pharma manufacturers and wholesalers on a blockchain to verify drug returns and compliance with the U.S. Drug Supply Chain Security Act (DSCSA). Early results indicate improved coordination and significant potential to eliminate counterfeit drugs from the supply chain by verifying each transaction's authenticity (Wang et al., 2021). Ghadge et al. (2023) provide a detailed analysis of blockchain implementation in pharmaceutical supply chains, highlighting benefits such as improved temperature monitoring for cold-chain drugs via sensor integration, automated reconciliation of records between manufacturers and distributors and enhanced patient safety through rapid recall capabilities (Ghadge et al.,

2023). Their framework suggests that when blockchain is combined with supporting technologies (IoT for condition tracking, AI for demand forecasting), it can create a more secure and efficient pharma supply chain that not only reduces fraud but also optimises inventory levels and reduces waste.

Another critical healthcare application is in vaccine distribution, as seen during COVID-19. Some pilot programs used blockchain to track vaccine batches, verifying storage conditions and timely delivery. Blockchain's ability to create an indelible audit trail is extremely valuable here – it can prove that a vaccine vial was kept within required temperature ranges throughout transit (when IoT sensor data is logged on-chain) and can authenticate that the administering clinic received genuine stock from an authorised source. Research by Upadhyay et al. (2021) on sustainable supply chains notes that blockchain increases accountability in healthcare networks and can improve social sustainability by ensuring medicines are authentic and equitably distributed. All these developments indicate that the healthcare and pharma sectors view blockchain as a “quantum of trust” technology (Upadhyay et al., 2021), with a strong focus on traceability and compliance. Going forward, integration with hospital information systems and regulators' databases will be important to realise the full benefits.

Manufacturing and Industrial Supply Chains

Manufacturing supply chains, including automotive, aerospace and electronics, are complex networks with multiple tiers of suppliers. These sectors face challenges like counterfeit parts, inefficient manual processes for procurement and tracking and difficulty in coordinating across suppliers. Blockchain has been introduced as part of the industry 4.0 toolkit to create transparent and efficient manufacturing ecosystems. Pournader et al. (2020) conducted a systematic review covering manufacturing and other sectors, concluding that blockchain can streamline supplier certification, track components for quality control and facilitate just-in-time manufacturing by improving data flow across the chain. For example, an aerospace manufacturer can use a blockchain network to ensure all parts (from bolts to avionics) are sourced from approved vendors, with each part's origin and

inspection certificates logged immutably. If a defect is found, the manufacturer can trace back to the exact batch and supplier in minutes, pinpointing root causes far more efficiently than traditional paper trails allow.

In the automotive industry, companies like BMW and Mercedes have explored blockchain for material provenance (e.g., to ensure ethical sourcing of minerals like cobalt) and for odometer fraud prevention (logging vehicle mileage on a blockchain to prevent tampering). A conceptual study by Manupati et al. (2020) proposed a blockchain-based multi-echelon model that optimised emissions and costs under a carbon tax policy, demonstrating that blockchain can support sustainable manufacturing by providing data needed for carbon tracing and enabling greener decision-making. Essentially, blockchain can give manufacturers a granular, trustworthy view of their entire supply chain – from raw materials to finished goods – which is invaluable for quality assurance, compliance (like proving conflict-free minerals or adherence to labour standards) and efficiency gains.

Blockchain is also being intertwined with industrial IoT (IIoT) on the factory floor. For example, equipment sensors can write operational data (like machine maintenance logs or output counts) directly to a blockchain, creating a tamper-proof record of production. This can automate audit processes for standards like ISO 9001. Kshetri (2018) emphasised IoT's role in blockchain solutions, noting that IoT devices are increasingly being incorporated to validate identities of assets and record environmental conditions, thereby bolstering the reliability of blockchain data in manufacturing. A practical instance is Bosch's blockchain-based system for logging sensor data of critical components, which improves trust in quality data shared with upstream suppliers and downstream OEMs.

Logistics and Transportation

Global logistics – encompassing shipping lines, freight forwarding, warehousing and last-mile delivery – is a backbone of supply chains that has historically been paper-heavy and prone to coordination issues. Blockchain has begun to streamline logistics by creating secure digital platforms for data exchange among carriers, ports, customs and manufacturers. The most notable example is the TradeLens platform (a collaboration initially between

IBM and Maersk), which uses blockchain to connect participants in international shipping. By 2020, TradeLens had over 100 participants including port operators and carriers, and it demonstrated the ability to cut document processing time and reduce shipping delays by providing a single, shared view of shipment statuses and documents. Academic research mirrors these developments: Hakimi et al. (2020) found that blockchain applications in transport can lead to improved supply chain visibility and efficiency, especially when dealing with multi-modal transport and cross-border movements (Sabeti et al., 2019). They documented that blockchain-enabled platforms reduce the time trucks spend waiting at ports by automating cargo release and customs approvals via smart contracts, which trigger once all digital documents are in place.

Another logistics use-case is cold chain monitoring for perishable goods. Blockchain solutions (like those by OriginTrail or Modum) attach IoT temperature sensors to shipments and log the sensor readings on a blockchain. If a threshold is exceeded, the smart contract can flag it and even notify insurance automatically. This ensures accountability: all parties see the same temperature log and cannot dispute if a spoilage event occurred. Rogerson and Parry (2020) reported that in their food case studies, such an approach significantly improved food supply chain visibility, giving stakeholders confidence in product quality upon arrival (Rogerson & Parry, 2020).

In addition, the trucking and freight sector has looked to blockchain for streamlining freight brokerage. Startups have used blockchain to match shippers with carriers (like a decentralised Uber for trucks) and to ensure quick freight payment upon delivery, using stablecoins or tokenised payments that release through a smart contract. This addresses long-standing problems of payment lags in the trucking industry. Gurtu and Johny (2019) note that blockchain holds the potential to reduce such inefficiencies in logistics by disintermediating brokers and fostering direct trust between shipper and carrier. While full disintermediation is yet to be achieved, we are seeing steps in that direction with logistics consortia forming around blockchain standards (e.g., the Blockchain in Transport Alliance, BiTA, which standardises data formats for blockchain freight apps).

In summary, across logistics and transportation, blockchain has started to cut through the complexity by

providing a shared, reliable data infrastructure. It enhances container tracking, simplifies customs and ensures data consistency across all players. These improvements lead to lower lead times, reduced losses (from theft or spoilage) and better utilisation of assets. The continued development of industry-wide blockchain platforms and interoperability between them will likely define the next phase of innovation in logistics.

Emerging Trends

As we reach 2025, blockchain in SCM stands at an interesting juncture. The initial hype has settled, several large projects have yielded mixed outcomes, yet the fundamental potential remains and technology continues to evolve. In this section, we discuss emerging trends, recent innovations and future prospects for blockchain's role in SCM. These include technological advancements, integration with other emerging technologies and shifts in industry adoption patterns.

Integration with IoT and AI Technologies

The convergence of blockchain with the Internet of Things (IoT) and Artificial Intelligence (AI) is unlocking new possibilities for supply chain optimisation. IoT integration addresses the challenge of getting authentic, real-time data into blockchains. Sensors and devices can automatically record events (e.g., a pallet's temperature, location, humidity, or shock exposure) and push that data to a blockchain ledger without human intervention. This synergy creates a digital supply chain that is self-monitoring. Lin et al. (2020) underscore that the integration of IoT devices with blockchain enhances transparency and trust by providing real-time, verifiable tracking of goods. In an agricultural system, for instance, IoT sensors in a grain silo can record temperature and moisture levels on a blockchain, assuring all stakeholders that storage conditions remained within safe thresholds (preventing spoilage). If any reading goes out of range, alerts can be triggered instantly to relevant parties via smart contract logic. This level of automated, trustworthy monitoring was previously unattainable with siloed databases.

Similarly, in high-value manufacturing, IoT sensors on machines can log production data (operational hours, maintenance performed, output quality metrics) to a

blockchain, creating an immutable equipment log. When a product defect is traced, AI algorithms can analyse this rich data to find correlations (e.g., a machine that had a temperature spike produced the defective batch) and proactively prevent future issues. The blockchain ensures the data feeding the AI is trustworthy. Tsolakis et al. (2023) explore the joint implementation of AI and blockchain in a tuna fish supply chain, demonstrating that AI-driven analytics combined with blockchain-verified data can significantly extend performance boundaries and drive sustainable practices. In their case, AI was used to optimise fishing schedules and routes, while blockchain tracked the tuna from catch to market to guarantee provenance and freshness. The integration meant decisions recommended by AI could be trusted and audited via the blockchain record, and sustainability claims (like certified fishing methods) were transparent to all stakeholders (Tsolakis et al., 2023).

AI also benefits from blockchain by addressing data integrity concerns. Many AI models (for demand forecasting, supplier risk assessment, inventory optimisation) need vast amounts of supply chain data. If this data is fragmented or unverified, the AI outcomes can be flawed. Blockchain can provide a single, reliable data source by aggregating inputs from different players on one ledger. Upadhyay et al. (2022) note that such data sharing, when incentivised properly, allows advanced analytics to generate insights that benefit the entire chain (for example, predicting shortages or optimising routes). In essence, blockchain can serve as the secure data infrastructure on top of which AI and machine learning algorithms can run confidently. Moreover, blockchain can even host decentralised AI algorithms (through smart contracts) that automatically execute decisions when certain conditions in the data are met – creating a self-driving supply chain system.

One emerging concept is the “autonomous supply chain,” where IoT sensors sense, blockchain logs and AI decides, with minimal human involvement in routine transactions. For instance, a smart warehouse could detect inventory running low (IoT), verify via blockchain that demand is genuine and no fraud is occurring, then trigger an AI-driven procurement order which is executed via a smart contract with a supplier. We are not fully there yet in practice, but pilot projects are showing elements of this vision. Choi et al. (2020) emphasised in their editorial on

digital supply chains that the combined effect of IoT, AI and blockchain is greater than their individual impacts, as each technology addresses the other's limitations. IoT provides data, blockchain ensures data trust and process automation and AI provides intelligence – together leading to more resilient, agile and efficient supply chains.

Sustainability and the Circular Supply Chain

Sustainability has become a paramount objective in modern SCM – companies are aiming for lower carbon footprints, ethical sourcing and adherence to environmental regulations. Blockchain offers unique capabilities to further these sustainability goals by enabling transparency and accountability in how products are sourced, produced and recycled. Saberi et al. (2019) discuss the relationships between blockchain and sustainable SCM, suggesting that blockchain can help overcome informational barriers and misaligned incentives that often impede sustainability initiatives. For example, a major challenge in ensuring a sustainable supply chain is verifying that suppliers at all tiers comply with environmental standards (e.g., no illegal deforestation, proper waste handling) – something that companies have historically struggled to monitor. With blockchain, certifications and audits can be recorded immutably; a supplier could upload a government-validated sustainability certificate onto a shared ledger, making it visible to all downstream buyers. If a supplier's certification lapses or a violation is reported, that too can be logged, creating pressure for improvement or allowing for swift corrective action.

Upadhyay et al. (2022) conducted a comprehensive review of high-quality research on blockchain for sustainable SCM, finding that blockchain initiatives largely cluster around three themes: (1) supporting sustainable business practices (e.g., fair trade, ethical sourcing), (2) serving as decision support for sustainability-related decisions (like optimising logistics to cut emissions) and (3) enabling sustainable intelligent transportation systems. Across these themes, blockchain's role is to provide trusted information that stakeholders (including consumers, regulators and partners) can rely on to evaluate sustainability claims. One prominent example is the use of blockchain in verifying carbon credits and footprints: companies can

log carbon emissions data for each batch of product on a blockchain. When a product is sold, the embedded carbon footprint is known and verifiable, enabling mechanisms like carbon labelling for consumers or automated carbon credit trading via smart contracts.

The circular economy – which emphasises recycling, remanufacturing and reducing waste – also stands to gain from blockchain. Kouhizadeh et al. (2019) argue that blockchain can facilitate closed-loop supply chains by tracking products through their end-of-life and ensuring responsible disposal or reuse. For instance, an electronics manufacturer might use blockchain to track a component from production to the consumer and then through a returns process back to recycling. This provides a transparent record that the component was properly recycled, which can be audited for regulatory compliance and sustainability reporting. Meyer et al. (2019) even envisioned using blockchain to implement the Physical Internet concept for greener logistics, where smart contracts dynamically route freight through the most energy-efficient paths (like ride-sharing for cargo) and automatically account for emissions.

On the social sustainability front, blockchain brings traceability of labour practices. Consumers and watchdogs are increasingly interested in whether forced or child labour was involved in making a product. Blockchain cannot prevent bad labour practices by itself, but it can create an immutable log of a product's journey which, combined with IoT and manual audits, can deter unscrupulous suppliers from engaging in forbidden practices – since records can be checked and anomalies (like an unrealistic production volume that hints at labour abuse) can be flagged. Some pilot projects in the textile industry use blockchain to allow consumers to see if their garment passed through factories audited for fair labour. van Hoek (2019) noted in an implementation study that beyond technology, blockchain initiatives often drive governance changes – companies establish new standards for data sharing and accountability among partners, which inherently supports sustainability goals (because there is less hiding of unsustainable behaviour when data is shared).

In summary, blockchain is emerging as a “sustainability enabler” in supply chains by providing the data infrastructure needed for credible sustainability

programs. It helps verify green claims, coordinates multi-party sustainability efforts (like industry-wide recycling programs) and empowers consumers and regulators with reliable information. The period 2018–2025 has seen many proof-of-concept projects in this vein, and recent literature is optimistic that scaling these solutions could significantly contribute to achieving global sustainability targets in supply chain operations (Sabeti et al., 2019; Lohmer et al., 2020). Nonetheless, challenges like ensuring the accuracy of sustainability data on the blockchain and integrating with legacy environmental reporting systems remain areas for future development.

Technical and Adoption Challenges

While the potential of blockchain in SCM is well-demonstrated, real-world adoption has faced several technical and organisational challenges. Researchers have systematically identified these barriers. Sabeti et al. (2019) classify blockchain adoption barriers into four categories: intra-organisational (internal to a firm, e.g., lack of skills or resistance to change), inter-organisational (among firms, e.g., misaligned incentives in the supply chain), technical (scalability, integration, etc.) and external (regulatory hurdles, market uncertainty). Each category presents issues that must be addressed for successful implementation.

On the technical front, scalability and performance are prime concerns. Early blockchain platforms (like Bitcoin and public Ethereum) were not designed for high transaction throughput, leading to slow processing and high energy use when naively applied to supply chains with thousands of daily transactions. Newer enterprise-grade blockchains and Layer-2 solutions have improved throughput, but concerns remain about whether a global-scale supply chain network can operate smoothly on a blockchain without bottlenecks. Casino et al. (2019) highlight interoperability as a problem – many different blockchain systems exist, and lack of standards means if Company A is on one platform and Company B on another, linking their systems is non-trivial. This leads to standardisation issues, analogous to EDI standard mismatches in earlier decades. Efforts like the Blockchain in Transportation Alliance are working on standards, but until widely adopted protocols emerge, this slows multi-company onboarding.

Data privacy is another technical challenge. Supply chains often involve sensitive commercial data (prices, supplier identities, etc.). Companies may be reluctant to share this on a blockchain visible to competitors or even partners. Techniques like permissioned blockchains (where only authorised parties see certain data) and data encryption on-chain help, but they add complexity. Min (2019) noted that firms in developing regions might also face infrastructure issues – unreliable internet, low IT penetration – which hamper blockchain's effectiveness. If every node in a supply chain needs to run a blockchain node, under-developed partners could struggle, creating a digital divide issue. Indeed, poor digital infrastructure and lower IT maturity in smaller suppliers can “defeat the purpose of blockchain implementation” if not accounted for.

Organisationally, one of the biggest hurdles is adoption cost and ROI uncertainty. Implementing blockchain requires investment in new systems, training personnel and possibly redesigning processes. Many companies ask: who bears these costs and who gains the benefits? In a fragmented supply chain, the party who invests in the system might not capture proportional benefit unless all others join – a classic collective action problem. Hald and Kinra (2019) observed that managers are often stuck in a wait-and-see approach: everyone wants others to invest first, leading to a stalemate (Hald & Kinra, 2019). To overcome this, some supply chains have seen powerful anchor companies (like Walmart in food or Maersk in shipping) drive the initiative, essentially forcing or incentivising partners to adopt. But this power dynamic can cause friction if smaller partners feel burdened.

Another challenge is cultural and process change. Blockchain implementation often requires supply chain partners to agree on new ways of working, more transparency and sharing data they might have kept proprietary. This can challenge existing power structures or raise concerns about data misuse. Schmidt and Wagner (2019) called blockchain in supply chains an “unfulfilled promise” at the time, largely due to these consensual trust issues – ironically, a technology designed to eliminate the need for trust still requires trust to initially convince parties to join the network (Schmidt & Wagner, 2019). Companies worry about what happens if something goes wrong – e.g., erroneous data on a blockchain, or a smart contract bug causing losses – and how liability is handled.

The legal frameworks for smart contracts are still catching up; questions of jurisdiction and enforceability linger.

Security, paradoxically, is both a driver and a challenge. While blockchain itself is secure, the applications around it (wallets, interfaces, etc.) can be vulnerable. If a hacker gains access to a supply chain participant's key, they could manipulate records or cause disruptions. Ensuring robust cybersecurity and governance is essential. Lacity (2018) emphasises addressing these key challenges

(interoperability, scalability, privacy, legal) to move enterprise blockchain from pilot to production.

Finally, there is the question of energy efficiency, especially for proof-of-work blockchains. Most supply chain projects use permissioned chains with more efficient consensus (PoA, PoS, etc.), but environmental impact of blockchain infrastructure is a consideration aligning with sustainability goals. Table 5 summarises some of these key challenges and potential mitigation strategies being explored.

Table 5: Key Challenges of Blockchain in Supply Chain Management and Mitigation Approaches

Challenge	Description	Potential Mitigation Strategies
Scalability & Throughput	Blockchain networks may not handle high transaction volumes or speed required for large supply chains. Network congestion and latency can hinder real-time use.	– Use of scalable ledger technologies (e.g., Proof-of-Stake, sharding, Layer-2 networks) (Zeng et al., 2019). – Off-chain data storage with on-chain hashes (reduces on-chain load). – Batch processing of events (recording summaries instead of every item) to lower transaction frequency.
Interoperability & Standards	Difficulty connecting different blockchain systems and integrating with legacy SCM software. Lack of common data standards across participants.	– Development of blockchain interoperability protocols and APIs (e.g., Interledger, standard adapters for ERPs) (Vadgama & Tasca, 2021). – Industry consortia defining common data models (GS1 standards for product info on blockchain, etc.). – Middleware platforms that can interface with multiple blockchains, providing a unifying layer.
Data Privacy & Confidentiality	Companies fear exposing sensitive business data on a shared ledger. Need to control who can see what in a multi-party network.	– Use of permissioned blockchains with access control layers (Hussain et al., 2021). – Advanced cryptographic techniques: zero-knowledge proofs, encryption of data on-chain, and sharing keys only with authorized parties. – Partitioning data: e.g., using channels or sidechains for competitor-sensitive data, while publishing common traceability info on main chain.
Integration with Legacy Systems	Challenge of connecting blockchain to existing enterprise systems and processes. Risk of duplicate work or errors during transition period.	– Invest in robust APIs and integration tools that allow automatic flow of data from ERP/WMS to blockchain and vice versa. – Gradual rollout approach: parallel pilot runs to iron out integration issues before full switch. – Training IT staff or using vendors experienced in system integration for blockchain (since it's a new skillset).
High Implementation Costs	The cost of technology, development, and operation might be high, especially if ROI is unproven. Small players may lack resources.	– Start with targeted use-cases that promise clear ROI to justify costs, then expand. – Use open-source and cloud-based blockchain services to reduce upfront infrastructure cost. – Consortium cost-sharing models: large firms may subsidize onboarding of smaller partners (e.g., providing them with cheap/free access tools) because the value increases with network size.
Regulatory & Legal Uncertainty	Unclear legal recognition of blockchain records and smart contracts in different jurisdictions. Compliance issues (e.g., GDPR vs immutable ledger).	– Engage with regulators through sandbox initiatives and pilots to shape supportive regulations (Lopez, 2022). – Use hybrid solutions that can comply with regulations (e.g., avoid storing personal data on-chain to comply with GDPR, store references instead). – Adopt legal clauses that recognize blockchain data in contracts between parties (private law solutions while public law catches up).
Adoption & Collaboration (Consortium Management)	Difficulty in getting all stakeholders to participate and change their processes. Potential reluctance due to perceived loss of control or unequal benefits.	– Clearly articulate value proposition to each stakeholder group; possibly design incentive mechanisms (discounts, access to data) to encourage participation. – Ensure neutral governance: involve an independent third party or equal voting rights in network governance to build trust (Lopez, 2022). – Phased approach: onboard key influential players first (anchors), then leverage them to bring in others (e.g., Walmart's mandate forced suppliers to join). – Provide easy-to-use tools and support (lower the technical barrier for entry).

In summary, the path to broad blockchain adoption in SCM is gated by a mix of technical limitations and human factors. Progress from 2018 to 2025 has been steady – many technical issues (like transaction speed) are being mitigated by new platforms (Hyperledger Fabric, Corda, Polygon, etc.), and there's a greater willingness among firms to collaborate on blockchain consortia given the success of early pilots. Still, overcoming standards fragmentation and building industry-wide trust frameworks remains work in progress. Scholars frequently call for more case studies and pilot analyses to demonstrate clear ROI and for the development of governance models that fairly distribute costs and benefits among all supply chain participants (Saber et al., 2019; Upadhyay et al., 2022). These efforts will be crucial to reach the tipping point of widespread adoption.

Future Directions

Looking ahead, blockchain's role in SCM is expected to grow and evolve in tandem with other emerging technologies and changing market needs. One future direction is the development of interoperable blockchain networks or a "network of networks." Given the proliferation of platforms, research is focusing on cross-chain solutions that allow value and information to transfer between different blockchains. This could take the form of standardised protocols or middleware that connect, say, a food traceability blockchain with a finance/trade blockchain to enable combined functionality (e.g., automatic payment upon proof of delivery across systems). The IEEE and other standards bodies are actively exploring standards in this space, and some scholars argue that achieving seamless interoperability will unlock the next level of supply chain automation and visibility.

Another key area is scaling up consortium networks. Many current successful projects are within a single supply chain or a small network of known partners. Future research and pilots aim to scale this to industry-wide utilities. For example, one can envision a global blockchain for food safety that many companies contribute to and rely on, or a pharmaceutical blockchain backbone that every drug manufacturer and regulator uses worldwide. van Hoek (2020) notes the research opportunity in examining how such large-scale networks could be governed and how

data from blockchain can be integrated into decision-making to create more resilient post-COVID supply chains. The pandemic indeed highlighted the need for resilience and real-time data sharing – blockchain is seen as part of that solution, but scaling it requires addressing governance (who runs the network?) and economic models (subscription fees, data ownership rights, etc.).

The integration of blockchain with AI and machine learning will deepen. Future supply chains might use blockchain not just as a passive ledger but as an active data layer feeding AI models that, through smart contracts, can automatically execute decisions. We expect to see more work on algorithmic SCM – for instance, using blockchain to facilitate automated negotiations between AI agents representing different firms (autonomous supply chain procurement). Tsolakis et al. (2023) have already proposed frameworks for AI-blockchain synergy in specific supply chains, and this concept could broaden to multi-industry ecosystems. Additionally, edge computing and local blockchains might handle IoT data at the source, summarising and sending critical info to main blockchains to reduce data overload – this aligns with the trend of decentralising not just data storage but computing.

From a sustainability and regulatory perspective, blockchain could become a standard tool for compliance. It's plausible that regulators might mandate or endorse blockchain-based traceability for certain industries (like food and pharma) by 2030. This top-down push would accelerate adoption. Research by Behnke and Janssen (2020) suggests that to truly improve traceability (especially in food), certain boundary conditions like data governance and incentive alignment must be met. Future studies will likely explore how policy can create those conditions, perhaps via public-private partnerships where regulators partially host or oversee industry blockchains to ensure neutrality and compliance enforcement.

Another exciting direction is the tokenisation of supply chain assets and blockchain-based supply chain finance. By tokenising real assets (inventory, warehouse receipts, etc.), blockchain could enable new financing models such as inventory being used as collateral in near real-time or dynamic discounting through token exchange. Some pilots have shown that small suppliers can get better access to credit if their receivables and performance

history are recorded on a blockchain that financiers trust (because the data is immutable and verified by the buyer's confirmations). This democratisation of supply chain finance via blockchain is a nascent area that combines FinTech with SCM; we anticipate more peer-reviewed studies evaluating its impact on liquidity and resilience for SMEs in supply chains.

Finally, researchers point out the need to address social implications and ethical design as blockchain pervades supply chains. For instance, Manski (2017) questioned whether blockchain will create a technological commonwealth that empowers smaller actors or just reinforce existing power structures with a new tool. Early evidence is mixed – technology can empower, but it can also be used for surveillance or control if not checked. Future work will need to examine how to design blockchains that are inclusive (ensuring all members, even small farmers or suppliers in developing countries, can participate and benefit) and how to manage the wealth of data generated in a way that respects privacy and competitive boundaries.

Conclusion

The period 2008–2025 laid the foundation, proving blockchain's value in enhancing transparency, efficiency and sustainability of supply chains. The next era will likely see consolidation of platforms, more pervasive adoption as technical and trust barriers fall and deep integration with AI/IoT to usher in truly intelligent, autonomous supply chain networks. The vision is a supply chain ecosystem where information silos are eliminated, transactions execute with minimal friction, sustainability is verified at each step and the system can adapt rapidly to disruptions – blockchain is a key enabler of that vision, continuing to shape modern SCM well beyond its first 17 years of innovation.

AI Use Declaration

AI application was used for editorial and formatting purpose for this review article. The author independently read and verified all cited sources and ensured that summaries accurately reflected the original texts.

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