

Blockchain Technology in Supply Chain Management: Enhancing Transparency, Traceability, and Sustainable Performance

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Abstract

Supply chains have become increasingly global, multi-tiered, and data-dependent. This complexity creates persistent problems involving limited product visibility, fragmented information systems, counterfeit goods, delayed recalls, weak supplier coordination, and difficulties in demonstrating sustainability compliance. Blockchain technology has gained attention as a potential mechanism for improving the reliability and accessibility of supply-chain information. By maintaining a distributed, tamper-resistant ledger, blockchain can record product movements, ownership changes, quality data, certifications, and transaction events across multiple organizations. This paper presents a structured literature review of blockchain applications in supply chain management, with emphasis on transparency, traceability, smart contracts, and sustainable supply-chain performance. The review synthesizes findings from key studies on blockchain-enabled supply-chain architectures, traceability frameworks, textile and clothing applications, automotive supply chains, and implementation challenges. The findings indicate that blockchain can improve information sharing, provenance verification, auditability, product recall capability, and stakeholder trust. However, its benefits are conditional on trustworthy input data, interoperability with existing systems, appropriate governance, collaboration among supply-chain partners, and compliance with privacy and legal requirements. The paper also proposes a conceptual blockchain-enabled supply-chain framework consisting of data capture, validation, blockchain network, smart-contract, and application layers. It concludes that blockchain should not be considered a replacement for all supply-chain systems; rather, it should be adopted where multiple stakeholders require shared, secure, and verifiable records.

Keywords— Blockchain; supply chain management; traceability; transparency; smart contracts; sustainability; Industry 4.0.

I. Introduction

A. Background

Supply chain management (SCM) involves the coordination of materials, information, finances, and services from raw-material suppliers to final consumers. A typical supply chain includes suppliers, manufacturers, logistics providers, distributors, retailers, regulators, and customers. These actors often use separate databases, enterprise resource planning systems, spreadsheets, paper records, and communication platforms. Although such systems support day-to-day operations, they may create information silos and make end-to-end visibility difficult.

The growing globalization of production has increased this challenge. A single product may include raw materials from one country, processing activities in another, manufacturing in a third location, and distribution across several markets. As the number of supply-chain actors increases, it becomes harder to determine where a product originated, whether it was stored under required conditions, whether it has been altered, and whether its suppliers complied with quality, social, or environmental standards. These issues are especially relevant in food, pharmaceuticals, automotive components, textile and apparel, electronics, and luxury goods.

Traditional SCM systems often depend on one central organization or a trusted intermediary to store and verify transaction records. This arrangement can create delays, duplicated data entry, limited information access, and disputes

about the accuracy of records. For example, when a contaminated food product is detected, an organization may need substantial time to identify the responsible supplier, batch, transportation route, and affected retail locations. Similarly, a counterfeit product may be difficult to distinguish from an authentic item when provenance records are incomplete or easily altered.

Blockchain technology has emerged as a potential response to these concerns. Blockchain is a distributed ledger technology in which authorized participants share records of transactions or events. Each new record is linked cryptographically to previous records, making unauthorized modification more difficult. Rather than relying on a single database controlled by one organization, blockchain enables multiple participants to access and validate a common version of selected supply-chain information. This feature can improve transparency, traceability, accountability, and trust among organizations that may not fully trust one another.

The relevance of blockchain to SCM is not limited to cryptocurrency or financial transactions. Its main supply-chain value lies in its ability to create a reliable history of product-related events. Such events may include sourcing, production, inspection, packaging, shipment, delivery, ownership transfer, and disposal. When combined with technologies such as radio-frequency identification (RFID), global positioning systems (GPS), Internet of Things (IoT) sensors, QR codes, cloud platforms, and artificial intelligence, blockchain can support more responsive and data-driven supply-chain operations.

However, blockchain adoption is not automatically beneficial. It may involve high implementation costs, integration difficulties, privacy concerns, legal uncertainty, governance conflicts, scalability limitations, and energy-use concerns. In addition, blockchain protects the integrity of stored data but cannot guarantee that the original data entered into the system are correct. If inaccurate sensor readings, false certifications, or manipulated manual inputs are added to a blockchain, the resulting record may remain permanently inaccurate. Therefore, blockchain must be assessed as part of a broader supply-chain governance and data-quality strategy.

B. Problem Statement

The primary problem addressed in this paper is the lack of trusted, shared, and end-to-end information in complex supply chains. Traditional centralized systems may not provide all stakeholders with timely access to reliable product data. This limitation can affect product traceability, quality assurance, inventory visibility, recall management, regulatory compliance, sustainability reporting, and consumer confidence.

The existing literature suggests that blockchain can strengthen supply-chain transparency and traceability, but its practical adoption remains at an early stage [1], [2]. Many studies are conceptual, exploratory, or focused on a single industry. There is therefore a need to synthesize the current literature, identify the main benefits and barriers, and propose a practical framework for blockchain-enabled supply-chain management.

C. Research Objectives

The objectives of this paper are:

1. To examine the role of blockchain technology in supply-chain management.
2. To analyze how blockchain can improve supply-chain transparency and product traceability.
3. To evaluate the relationship between blockchain adoption and sustainable supply-chain performance.
4. To identify technical, organizational, legal, and governance-related barriers to blockchain adoption.
5. To propose a conceptual framework for implementing blockchain in supply-chain operations.

D. Research Questions

This paper addresses the following research questions:

- RQ1: How can blockchain technology improve transparency and traceability in supply-chain management?

- RQ2: What are the major applications of blockchain across supply-chain activities?
- RQ3: How can blockchain contribute to economic, environmental, and social sustainability in supply chains?
- RQ4: What barriers limit blockchain adoption in supply-chain networks?
- RQ5: What conceptual framework can support the implementation of blockchain-enabled supply-chain systems?

E. Scope of the Study

This paper focuses on blockchain applications in supply-chain management rather than cryptocurrency trading or financial investment. It examines blockchain's use in product provenance, traceability, supplier coordination, logistics, smart contracts, sustainability reporting, and quality assurance. Particular attention is given to textile and clothing supply chains, automotive supply chains, and broader traceability applications.

The paper is based on a literature review and proposed conceptual framework. It does not claim to test a blockchain system, conduct an original survey, or report experimental findings. The recommendations should therefore be interpreted as literature-based insights rather than universal implementation rules.

F. Organization of the Paper

The remainder of this paper is organized as follows. Section II discusses blockchain technology and its conceptual relationship with SCM. Section III outlines the literature-review methodology. Section IV examines major blockchain applications in supply-chain operations. Section V analyzes transparency and traceability. Section VI discusses sustainable supply-chain performance. Section VII identifies adoption challenges and barriers. Section VIII presents a proposed blockchain-enabled supply-chain framework. Sections IX and X discuss research findings, gaps, and future directions. Section XI concludes the paper.

II. Background and Conceptual Foundations

A. Traditional Supply Chain Management

Traditional supply chains are designed to ensure that products, services, information, and funds move efficiently from suppliers to customers. Organizations use systems such as enterprise resource planning, warehouse management systems, transportation management systems, electronic data interchange, and supplier portals. These systems can be effective within a single company; however, they may not provide complete visibility across all supply-chain partners.

A major limitation of traditional SCM is data fragmentation. Each participant may maintain its own records, standards, processes, and levels of access. A manufacturer may know the identity of its first-tier supplier but may not have full information about lower-tier suppliers. Similarly, a retailer may know the product's delivery date but may not be able to verify all manufacturing or transportation conditions.

Another challenge is the reliance on manual verification and intermediaries. Certifications, invoices, bills of lading, quality reports, and customs documents are often checked by separate parties. This can increase processing time and administrative cost. It can also create opportunities for document manipulation, fraud, delayed reporting, and disagreement between supply-chain partners.

These weaknesses are especially significant when a product requires proof of origin, ethical sourcing, safe handling, or regulatory compliance. In the food industry, poor traceability can delay the identification of contaminated batches. In pharmaceuticals, weak records can increase counterfeit risk. In the textile sector, a lack of visibility may make it difficult to verify whether cotton was organically produced or whether labor conditions met stated standards. In the automotive industry, poor component-level traceability may complicate quality investigations and product recalls.

B. Blockchain Technology

Blockchain is a distributed digital ledger that records transactions or events in a sequence of cryptographically linked blocks. Each block contains data, a timestamp, and a cryptographic reference to the previous block. Once validated and

added to the chain, records become difficult to alter without detection. This structure supports data integrity and shared visibility among authorized participants.

Blockchain systems can be classified into three broad categories:

1. **Public blockchain:** A public blockchain can be accessed by anyone. It is highly decentralized but may create privacy, scalability, and transaction-cost concerns for business applications.
2. **Private blockchain:** A private blockchain is controlled by a single organization. Access is restricted, allowing greater control and confidentiality. However, it may offer less decentralization than public systems.
3. **Consortium or permissioned blockchain:** A consortium blockchain is managed by a group of authorized organizations. This model is often considered suitable for supply chains because participants can control access rights while sharing validated information across the network.

For supply-chain applications, permissioned or consortium blockchains are generally more practical. They allow suppliers, manufacturers, logistics companies, retailers, regulators, and auditors to access information according to their roles. For example, a consumer may only view a product's origin and sustainability certificate, whereas a regulator may access detailed compliance records.

C. Smart Contracts

Smart contracts are computer programs that execute predefined actions when specified conditions are met. In a supply chain, a smart contract may automatically release payment when goods are delivered and verified, send an alert when a temperature threshold is exceeded, or update ownership when a shipment reaches a destination.

Smart contracts can reduce the need for manual verification in routine transactions. For example, a shipment of perishable products may include IoT sensor data about temperature and humidity. If the recorded conditions meet the agreed threshold, the smart contract may confirm compliance. If the temperature exceeds the safe range, the system may flag the shipment for inspection or prevent automatic payment.

Despite these benefits, smart contracts require careful design. Business terms must be translated into clear digital rules, and legal responsibility must be defined when an automated contract executes incorrectly. Smart contracts should therefore be supported by human oversight, clear governance policies, and legal review.

D. Blockchain Integration with Industry 4.0 Technologies

Blockchain becomes more useful when integrated with other digital technologies. IoT devices can capture real-time data about product location, temperature, humidity, vibration, and handling conditions. RFID tags and QR codes can provide unique identities for products, batches, or packages. GPS devices can record shipment routes and delivery times. Cloud systems can store large volumes of non-sensitive data, while blockchain can store transaction proofs, timestamps, access permissions, and cryptographic hashes.

Artificial intelligence can also support blockchain-enabled supply chains. AI models can analyze demand patterns, detect unusual transactions, identify potential fraud, and predict supply disruptions. For example, an AI system may detect that a product's route differs significantly from its approved route. The blockchain ledger can then provide a verifiable history for investigating the anomaly.

However, the integration of blockchain, IoT, cloud computing, and AI creates additional technical requirements. Organizations must ensure that sensor data are accurate, interoperable, secure, and collected according to agreed standards. The quality of a blockchain system depends heavily on the quality of the data that enter it.

E. Traditional SCM Versus Blockchain-Enabled SCM

TABLE I

COMPARISON OF TRADITIONAL SCM AND BLOCKCHAIN-ENABLED SCM

Dimension	Traditional SCM	Blockchain-Enabled SCM
Data storage	Separate databases held by different organizations	Shared distributed ledger among authorized participants
Information visibility	Often limited to individual organizations or tiers	Role-based, near real-time visibility across the network
Traceability	May require manual reconciliation of records	Product events can be recorded in a chronological digital trail
Data integrity	Records may be changed or duplicated across systems	Cryptographic linking makes unauthorized alteration detectable
Trust mechanism	Intermediaries, audits, contracts, and bilateral relationships	Shared validation, permissions, cryptographic proofs, and smart contracts
Product recall	Potentially slow due to fragmented information	Faster identification of affected batches and supply-chain stages
Main risks	Data silos, errors, delayed updates, limited visibility	Scalability, privacy, governance, interoperability, and inaccurate input data

Table I shows that blockchain can address several limitations of traditional systems. However, it should not be assumed that blockchain is always required. A conventional centralized database may be more efficient when only one trusted organization needs to manage the data. Blockchain is more appropriate where multiple parties need shared, verifiable records and no single participant is trusted to control the complete system.

F. Blockchain, Trust, and Supply-Chain Governance

Trust is a central issue in supply-chain networks. Organizations may collaborate while also competing for profit, protecting confidential information, or negotiating contracts. Blockchain can reduce some trust-related costs by providing a common and verifiable record of agreed events. This does not eliminate the need for business trust, but it can reduce uncertainty regarding transaction history, product origin, and document authenticity.

Treiblmaier [6] argues that blockchain should be understood through established supply-chain and economic theories, including transaction-cost economics, principal-agent theory, resource-based views, and network theory. From this perspective, blockchain may reduce information asymmetry and monitoring costs, while also creating new costs related to governance, infrastructure, and adoption.

Similarly, Kshetri [7] highlights blockchain's potential contribution to cost reduction, quality improvement, speed, dependability, risk reduction, sustainability, and flexibility. These benefits are relevant only when the system is designed around a clear business problem. Organizations should therefore begin with questions such as: What information must be shared? Which stakeholders require access? What level of traceability is necessary? Who validates the data? How will privacy be protected? What happens when incorrect data are recorded?

[Figure 1 Placeholder: Traditional Supply-Chain Information Flow Versus Blockchain-Enabled Shared Ledger]

III. Research Methodology for Literature Review

A. Research Design

This study uses a structured literature-review approach to examine blockchain technology in SCM. A literature review is appropriate because blockchain adoption in supply chains remains an emerging research area, and the available studies include conceptual papers, systematic reviews, case studies, surveys, frameworks, and technical prototypes.

The review focuses on identifying common themes, applications, benefits, barriers, and research gaps. The objective is not to calculate statistical effect sizes or claim universal causal relationships. Instead, the review synthesizes how different researchers have examined blockchain's contribution to transparency, traceability, and sustainability.

B. Core Literature Sources

Five core sources were selected because they address complementary aspects of blockchain-enabled SCM. Jabbar *et al.* [1] examine supply-chain digitalization, technical challenges, standards, traceability, and future research directions. Sharabati and Jreisat [2] provide a recent review of blockchain implementation benefits and barriers. Ahmed and MacCarthy [3] focus on the scope and granularity of blockchain-enabled traceability. Rajak *et al.* [4] present a traceability framework using the textile and clothing industry as a case context. Kamble *et al.* [5] analyze blockchain's relationship with supply-chain integration and sustainable performance in the automotive industry.

Additional literature was used to strengthen the conceptual discussion of supply-chain objectives, adoption challenges, systematic reviews, and theoretical perspectives [6]–[10].

C. Search Terms and Screening Logic

The literature was organized using commonly used search terms such as:

- “blockchain and supply chain management”
- “blockchain supply chain traceability”
- “blockchain transparency in logistics”
- “blockchain sustainable supply chain”
- “smart contracts in supply chain”
- “blockchain textile supply chain”
- “blockchain automotive supply chain”
- “IoT and blockchain traceability”

The review prioritized peer-reviewed journal articles, conference papers, and established academic publications that focused directly on blockchain applications in SCM. Articles focused solely on cryptocurrency trading, speculative investment, or unrelated financial applications were excluded. Studies were also excluded when they did not provide a meaningful connection to supply-chain processes, logistics, traceability, sustainability, or operations management.

D. Thematic Analysis

The selected literature was analyzed under five broad themes:

1. Transparency and visibility: The ability of stakeholders to access consistent and verified supply-chain information.
2. Traceability and provenance: The ability to trace a product, batch, component, or document across supply-chain stages.
3. Operational efficiency and automation: The role of smart contracts, digital records, and real-time data sharing.

4. Sustainability and compliance: The use of blockchain to support ethical sourcing, environmental reporting, waste reduction, and regulatory verification.
5. Adoption barriers and governance: The technical, organizational, legal, financial, and privacy-related issues that limit implementation.

This thematic approach allows different types of studies to be compared without assuming that they use identical methods or industry contexts.

E. Summary of Core Studies

TABLE II
SUMMARY OF THE FIVE CORE LITERATURE SOURCES

Source	Context/Method	Major Contribution	Main Limitation
Jabbar <i>et al.</i> [1]	Review of blockchain-enabled supply chains	Explains digitalization, GS1 standards, traceability, adoption challenges, and future directions	Broad review; does not test a single implementation
Sharabati and Jreisat [2]	Literature review	Identifies benefits, implementation barriers, and adoption factors	Dependent on reviewed literature; limited primary data
Ahmed and MacCarthy [3]	Case-based analysis and workshop insights	Introduces the concepts of traceability width and depth	Focuses strongly on traceability scope
Rajak <i>et al.</i> [4]	Textile and clothing case framework	Demonstrates blockchain-based traceability for organic cotton and apparel	Industry-specific case context
Kamble <i>et al.</i> [5]	Automotive-industry empirical study	Connects blockchain, supply-chain integration, and sustainable performance	Findings may differ across countries and industries

F. Limitations of the Literature Review Method

This review has limitations. First, the selected studies represent a limited part of the rapidly expanding blockchain-SCM literature. Second, blockchain technologies and industry adoption practices evolve quickly, meaning that new platforms, regulations, and implementation cases may emerge after the reviewed publications. Third, the studies use different methods, sectors, and definitions of performance. Therefore, their findings should not be treated as directly comparable numerical results.

Nevertheless, the selected literature provides a useful foundation for understanding how blockchain may create value in supply chains and why implementation challenges remain significant.

IV. Applications of Blockchain in Supply Chain Management

A. End-to-End Product Traceability

End-to-end traceability is one of the most widely discussed blockchain applications in supply-chain management. Traceability refers to the ability to follow a product, component, batch, or material through different supply-chain stages. These stages may include raw-material extraction, processing, manufacturing, packaging, transportation, warehousing, retailing, consumption, and disposal. In traditional systems, information about these stages is commonly stored in separate organizational databases. As a result, reconstructing a product's journey may require manual communication between several firms.

Blockchain can create a chronological record of supply-chain events. Each authorized participant can add relevant information to the shared ledger, such as a batch number, production date, quality certificate, shipping document, location update, or delivery confirmation. The ledger does not necessarily need to store every large file or sensor reading.

In many practical designs, detailed documents are stored off-chain in secure databases or cloud platforms, while the blockchain stores a cryptographic hash, timestamp, ownership information, and reference to the original data. This approach helps preserve data integrity without overloading the blockchain network.

A product traceability system can provide benefits for manufacturers, retailers, regulators, and consumers. Manufacturers can verify raw-material sources and monitor supplier compliance. Logistics providers can provide evidence of shipment handling and delivery. Retailers can identify the affected stock during a recall. Regulators can access relevant compliance records. Consumers can scan a QR code to view selected information about product origin, certifications, and sustainability claims.

Ahmed and MacCarthy [3] emphasize that traceability should not be viewed as a single uniform capability. The practical value of blockchain-based traceability depends on both the width and the depth of information recorded. Traceability width refers to the number of supply-chain stages included, from upstream suppliers to downstream consumers. Traceability depth refers to the granularity of data captured at each stage. For example, a basic system may record only supplier name and delivery date, whereas a more advanced system may record lot numbers, quality-test results, sensor data, labor certificates, carbon-emission information, and ownership transfers.

Organizations must decide the required width and depth according to the supply-chain context. A low-value product may not require detailed item-level tracking. In contrast, pharmaceuticals, luxury products, food items, automotive components, and organic cotton may require detailed traceability because safety, authenticity, compliance, or customer trust is particularly important. Therefore, blockchain systems should be designed according to the actual business problem, rather than being adopted simply because blockchain is a popular technology.

B. Food and Agricultural Supply Chains

Food supply chains are highly suitable for blockchain-based traceability because food safety, origin, freshness, and storage conditions are important to producers, regulators, retailers, and consumers. Food products often travel through farms, processors, distributors, warehouses, stores, restaurants, and households. A contamination event or quality problem can affect many stakeholders, and the ability to identify the affected batch quickly is essential.

Blockchain can record data such as farm location, harvest date, processing facility, temperature conditions, storage information, transportation route, inspection results, and retail delivery. When combined with RFID tags, QR codes, and IoT sensors, blockchain can help create a digital history from farm to fork. For example, a temperature-sensitive dairy product may be monitored during transportation. If sensor data indicate that temperature exceeded the allowed threshold, the system can flag the product for inspection.

A blockchain-enabled food traceability system can improve recall management. Instead of recalling every product from a broad category, organizations may identify the specific batch, supplier, or distribution route associated with a safety issue. This can reduce waste, financial loss, and reputational damage. It can also improve consumer confidence because customers may access selected origin and quality information through a product label or QR code.

However, food traceability systems still face practical challenges. Small farmers and local suppliers may not have access to digital devices, reliable internet connections, or technical skills. Data may be entered manually, creating a risk of error or intentional falsification. In addition, stakeholders may be unwilling to share commercially sensitive information, such as supplier prices or production volumes. For this reason, access-control rules and clear governance mechanisms are essential.

C. Textile and Clothing Supply Chains

The textile and clothing industry involves long, globally distributed, and multi-tiered supply chains. A garment may involve cotton farmers, yarn producers, fabric mills, dyeing units, garment manufacturers, transport companies, brands, retailers, and consumers. This complexity makes it difficult for companies to verify the origin of raw materials, the authenticity of sustainability claims, or compliance with labor and environmental standards.

Rajak *et al.* [4] demonstrate how blockchain can be used to improve traceability in the textile and clothing industry. Their study focuses on the flow of information related to organic cotton and highlights the value of blockchain in

recording product provenance across supply-chain participants. A blockchain-based system can help verify whether cotton labeled as organic was sourced from an approved farm and processed through identified supply-chain stages.

This application can be particularly useful for brands that make claims about ethical sourcing, organic materials, recycled content, fair labor practices, or reduced environmental impact. If these claims are supported by verifiable records, consumers may have greater confidence in the product. Blockchain can also support anti-counterfeiting measures by assigning unique identifiers to products, batches, or high-value items.

Nevertheless, blockchain cannot independently guarantee that a textile product is truly organic or ethically produced. The system can preserve the records entered into it, but it cannot verify physical reality without reliable audits, certifications, inspections, and data-capture mechanisms. Therefore, blockchain should complement—not replace—physical verification and third-party certification.

D. Automotive Supply Chains

Automotive supply chains are characterized by complex supplier networks, thousands of components, strict quality requirements, and substantial recall risks. A vehicle manufacturer may purchase parts from first-tier suppliers, who themselves depend on lower-tier suppliers. When a defective component is identified, the manufacturer must determine which vehicles contain the affected part and which suppliers, production lots, or assembly lines were involved.

Blockchain can improve component-level traceability in automotive supply chains. Records can include supplier identity, component serial number, manufacturing date, quality-test result, shipment event, installation stage, and warranty information. If a defect is discovered, the company can trace the component back to its origin and forward to the specific vehicles or customers affected.

Kamble *et al.* [5] examine blockchain's relationship with supply-chain integration and sustainable performance in the automotive industry. Their findings indicate that blockchain can support information integration among supply-chain partners and contribute to sustainability-oriented performance. The automotive context is especially important because it demonstrates that blockchain can be applied beyond product tracing. It can also support supplier coordination, compliance monitoring, efficient documentation, and responsible sourcing.

For example, automotive firms may use blockchain to record information about raw materials such as cobalt, lithium, aluminum, steel, or recycled plastics. This can assist in verifying whether materials were sourced according to environmental and social standards. However, the success of such systems depends on supplier participation, consistent identification standards, reliable data, and agreement on who controls access to sensitive information.

E. Logistics, Transportation, and Shipment Tracking

Logistics operations involve the movement of materials and products through multiple transportation modes, including road, rail, sea, and air. A shipment may pass through ports, customs authorities, warehouses, freight forwarders, carriers, and distribution centers. Each handover creates a new event that must be recorded and verified.

Blockchain can support logistics by creating a shared record of shipment status, cargo ownership, customs documentation, delivery confirmation, and condition monitoring. Smart contracts may be used to automate certain activities. For example, a freight payment could be triggered when a shipment reaches an agreed location and the delivery is confirmed. Similarly, a smart contract may notify stakeholders if a container deviates from its planned route or if a temperature-sensitive product exceeds a safe temperature range.

Pournader *et al.* [10] identify transportation and logistics as important domains for blockchain research. Blockchain can potentially reduce document-processing delays, improve coordination, and support the secure sharing of logistics information. The technology may be valuable in international trade, where paperwork, customs procedures, and ownership transfers involve many organizations.

However, logistics systems often operate across countries with different laws, standards, and digital infrastructures. A blockchain platform used by one carrier or port may not be compatible with another system. The need for interoperability is therefore a major consideration. Industry standards, common data formats, and clear governance arrangements are required before blockchain can achieve large-scale benefits in logistics.

F. Anti-Counterfeiting and Product Authenticity

Counterfeit products create risks for consumers, brands, regulators, and supply-chain partners. The risk is especially high in pharmaceuticals, luxury goods, electronics, cosmetics, spare parts, and food products. Counterfeit goods may reduce revenue, damage brand reputation, and create serious health or safety concerns.

Blockchain can support anti-counterfeiting by creating a unique digital identity for each product or batch. This identity may be connected to a QR code, RFID tag, near-field communication tag, serial number, or digital certificate. At each supply-chain stage, authorized participants can record transfers of ownership or verification events. A consumer or retailer can then scan the product identifier to check whether it matches the official record.

The value of blockchain in anti-counterfeiting lies in the difficulty of altering the product's digital history without authorization. If a counterfeit product uses a false or duplicated code, the system may detect that the identifier has already been used or does not match the official supply-chain record. However, physical-digital linkage remains a challenge. A counterfeiter may copy a valid QR code from an original product and place it on a fake item. Therefore, blockchain-based authentication may need to be combined with secure physical tags, tamper-evident packaging, serial-number controls, and inspection procedures.

G. Quality Control and Compliance Management

Quality control is essential in supply chains involving food, medicines, automotive components, chemicals, electronics, and industrial equipment. Quality-related data may include test results, inspection certificates, maintenance records, handling conditions, and regulatory approvals. When these records are fragmented across multiple databases or paper documents, it can be difficult to verify whether quality requirements were met.

Blockchain can create a secure audit trail for quality-related events. A supplier may upload a quality certificate, a manufacturer may record an inspection result, and a logistics provider may record transportation conditions. Regulators or auditors can be granted permission to verify relevant records without receiving access to all commercially sensitive information.

This approach can reduce audit time and improve accountability. It may also support compliance with standards related to product safety, environmental management, labor practices, and material sourcing. Nevertheless, the validity of blockchain-based quality records depends on the trustworthiness of the data source. If quality data are entered manually without verification, the blockchain ledger can preserve incorrect information. Data-validation procedures, authorized roles, digital signatures, and independent audits remain necessary.

H. Inventory Visibility and Demand Coordination

Blockchain may also support inventory visibility and demand coordination. Supply-chain disruptions often become worse when firms lack accurate information about inventory levels, shipment status, and supplier capacity. Shared visibility can help partners coordinate replenishment, production planning, and delivery decisions.

For example, a retailer may share verified point-of-sale data with selected suppliers, while suppliers may share verified shipment and inventory information with manufacturers. Smart contracts may automatically trigger replenishment alerts when stock falls below a predefined threshold. Such systems could reduce delays and improve responsiveness.

However, inventory data are commercially sensitive. Firms may not be willing to share full details with all partners, especially competitors. Permissioned blockchain systems can address this concern by restricting access based on roles. A supplier may view demand forecasts relevant to its own products, while a retailer may view shipment status without accessing supplier cost information. This illustrates why access control and governance are central to blockchain-enabled SCM.

[Figure 2 Placeholder: Blockchain Applications Across the Supply-Chain Lifecycle]

V. Blockchain for Transparency and Traceability

A. Understanding Supply-Chain Transparency

Supply-chain transparency refers to the availability, clarity, and reliability of information about supply-chain processes, actors, materials, and product movements. Transparent supply chains allow stakeholders to understand where products come from, how they were produced, who handled them, and whether agreed requirements were met.

Transparency is increasingly important because consumers, regulators, investors, and civil-society organizations expect companies to demonstrate responsible sourcing and operational accountability. A company may claim that its products are ethically sourced, environmentally friendly, or produced under safe labor conditions. However, these claims may not be trusted unless they are supported by verifiable information.

Blockchain can improve transparency by allowing authorized parties to view a common record of selected supply-chain events. Instead of depending on separate reports from each organization, stakeholders can verify data recorded on the shared ledger. This can reduce information asymmetry between supply-chain partners.

However, transparency should not be confused with unrestricted disclosure. Supply-chain partners often need to protect confidential information, such as prices, supplier contracts, production capacity, customer data, and proprietary processes. Therefore, an effective blockchain system must balance transparency with confidentiality. Permissioned access, encryption, private channels, and role-based data visibility can help achieve this balance.

B. Traceability Dimensions: Width and Depth

Ahmed and MacCarthy [3] provide an important contribution by distinguishing between the width and depth of traceability. These two dimensions help organizations avoid designing systems that either collect too little information or create unnecessary complexity.

Traceability width concerns how far the traceability system extends across the supply chain. A narrow system may track only one stage, such as the movement of finished products from a manufacturer to a retailer. A wide system may include raw-material suppliers, processing units, manufacturers, logistics providers, retailers, consumers, and reverse-logistics actors.

Traceability depth concerns the level of detail captured at each stage. A low-depth system may record only basic transaction information, such as date, location, and sender. A high-depth system may record batch numbers, certificates, sensor readings, inspection reports, sustainability data, ownership records, and production conditions.

The appropriate level of width and depth depends on industry needs. For high-risk products such as medicines or safety-critical automotive components, wide and deep traceability may be justified. For low-value products, a simpler and less expensive system may be more appropriate. The design process should therefore begin with a clear definition of the traceability objective.

C. Data Integrity and Auditability

Blockchain's immutability feature can strengthen supply-chain data integrity. Once a transaction or event is validated and added to the blockchain, unauthorized modification becomes difficult because changes would be visible to network participants. This can support auditability by creating a historical record of when an event occurred, who recorded it, and what information was included.

For example, if a shipment is transferred from a logistics provider to a warehouse, the handover event can be recorded with a timestamp and digital signatures from both parties. If a dispute arises later, the parties can review the shared record. Similarly, an auditor may verify whether an inspection certificate existed at a specific time and whether it was linked to a particular batch.

Auditability can reduce the cost and time associated with document reconciliation. However, blockchain records should not be treated as automatically truthful. The system can demonstrate that a record was stored and has not been altered, but it cannot independently prove that the physical event occurred exactly as described. Reliable data capture, digital identity management, and physical inspection remain essential.

D. Consumer Trust and Product Provenance

Consumers increasingly seek information about product origin, safety, environmental impact, and ethical production. Blockchain can provide a mechanism for sharing selected provenance information with consumers. A QR code on a product package may allow a customer to view the origin of raw materials, production location, certification status, transportation history, or recycling instructions.

This approach can be especially valuable for organic food, premium coffee, seafood, cosmetics, luxury goods, and sustainable apparel. If product claims are supported by a verifiable supply-chain history, consumer trust may improve. Brands can use blockchain-enabled provenance systems to differentiate their products from competitors.

Nevertheless, companies should avoid using blockchain merely as a marketing label. If the underlying data are incomplete, inaccurate, or selectively disclosed, consumer trust may decline. The credibility of a provenance system depends on transparent governance, independent verification, understandable consumer communication, and reliable physical-to-digital links.

E. Role of IoT, RFID, GPS, and QR Codes

Blockchain alone cannot observe the physical movement or condition of products. It requires data from external sources. IoT sensors, RFID tags, GPS devices, QR codes, and barcode systems play a critical role in connecting physical products to digital records.

RFID tags can identify products or batches automatically. GPS devices can record shipment locations. Temperature sensors can monitor cold-chain conditions. QR codes can provide product-level access for consumers and retailers. These technologies generate data that can be stored directly on-chain or referenced through blockchain records.

The integration of IoT and blockchain can improve real-time traceability. For example, if a container carrying vaccines experiences a temperature excursion, the sensor can record the event and a blockchain system can make the information available to authorized stakeholders. A smart contract may automatically generate an alert or require inspection before the shipment is accepted.

However, IoT devices themselves can be vulnerable to malfunction, cyberattack, calibration errors, and data manipulation. Secure device management, regular maintenance, and validation procedures are necessary. The use of blockchain does not remove these risks; instead, it makes the governance of data sources even more important.

F. Conceptual Supply-Chain Traceability Matrix

TABLE III
CONCEPTUAL BLOCKCHAIN-ENABLED TRACEABILITY MATRIX

Supply-Chain Stage	Typical Data Recorded	Main Stakeholder	Blockchain Benefit
Raw-material sourcing	Supplier identity, origin, certification, batch number	Supplier, manufacturer, regulator	Provenance and ethical-sourcing verification
Manufacturing	Production date, component data, quality-test result	Manufacturer, auditor	Tamper-resistant production history
Packaging	Product ID, QR code, expiry date, packaging record	Manufacturer, distributor	Product authentication and batch identification
Transportation	Route, shipment time, temperature, handover event	Logistics provider, retailer	Condition monitoring and chain-of-custody evidence
Warehousing	Arrival time, storage conditions, inventory status	Warehouse operator, distributor	Inventory visibility and accountability

Retail	Delivery confirmation, shelf location, product status	Retailer, consumer	Faster recall and consumer information access
Reverse logistics	Return reason, recycling data, disposal record	Consumer, producer	recycler, Support for circular economy and waste tracking

G. Product Recall Management

Product recalls can be costly because they may involve product removal, regulatory action, customer notifications, reputation loss, legal liability, and operational disruption. In a traditional supply chain, identifying affected products may require checking multiple databases and paper records. This process can be slow, especially when the product has passed through several suppliers and distributors.

Blockchain can improve recall management by enabling faster identification of affected batches and supply-chain stages. If every product event is linked to a unique batch or serial number, companies can determine which products were produced using a particular raw material, transported through a specific route, or sold to specific locations.

This targeted approach can reduce unnecessary recalls and minimize waste. Instead of withdrawing all products in a category, companies may recall only the affected batch. However, this benefit depends on complete participation and accurate data capture. If some suppliers or logistics providers do not record their events consistently, the traceability chain may contain gaps.

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