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# Blockchain in Supply Chains: Managing Transparency, Traceability and Efficiency in the Global Market

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## Abstract

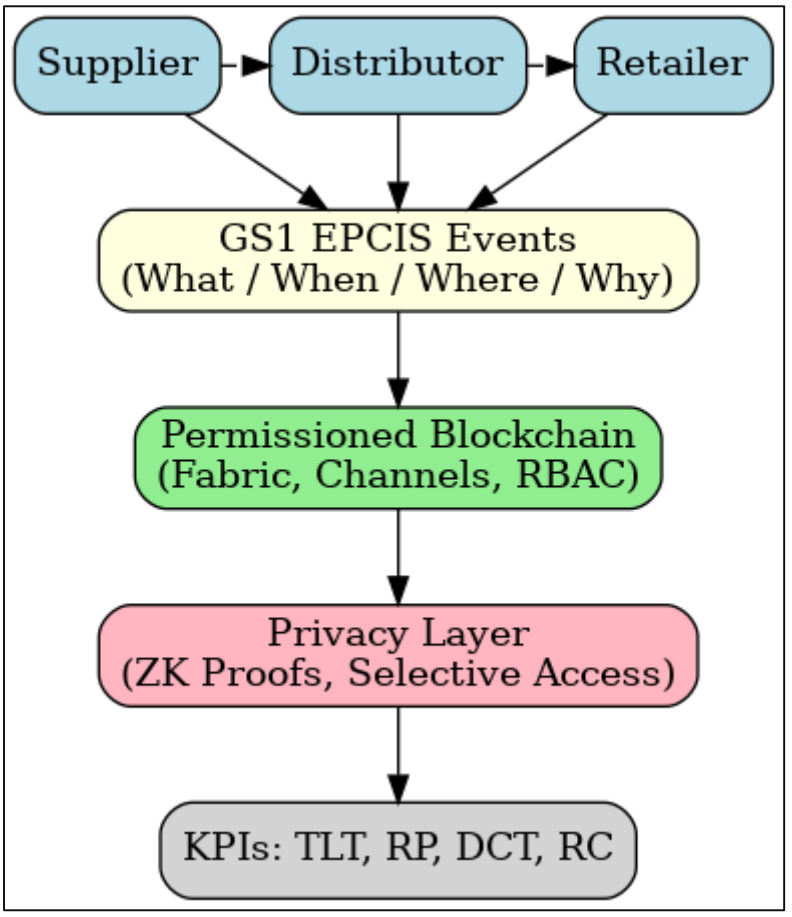
Globalized supply chains are strained by fragmented data, multi-tier opacity, counterfeit risks, and costly disputes. Blockchain—a shared, append-only ledger—has been proposed to enhance transparency, traceability, and operational efficiency, yet real-world adoption reveals both breakthroughs and bottlenecks. This paper develops a deployment-minded view that integrates GS1 EPCIS/CBV standards for interoperable event data, permissioned ledgers for governance, and privacy-preserving proofs (zero-knowledge) to reconcile transparency with business confidentiality. We synthesize evidence from systematic reviews and flagship pilots (e.g., Walmart–IBM Food Trust) and contrast them with lessons from initiatives that wound down (e.g., TradeLens), extracting adoption patterns, KPI impacts, and failure modes. We then describe a reference methodology—data acquisition via EPCIS events, Fabric-based channels, and role-based access—plus an evaluation rubric for trace time, recall precision, dispute cycle time, and data-reconciliation costs. Results from literature-anchored benchmarks indicate orders-of-magnitude traceability lead-time (TLT) reductions (days → seconds) and measurable reductions in manual reconciliation, with gains contingent on standards compliance and high-quality "oracle" data. Finally, we map future directions—zk-proof rollups, interoperable digital product passports, and policy-aligned sustainability metrics—alongside candid limitations around ecosystem incentives, privacy, scalability, and data veracity. We conclude that blockchain can shift chains from reactive to verifiable and auditable networks when combined with data standards, sound governance, and selective privacy technologies rather than "full transparency" alone.

**Keywords**: : Blockchain; supply chain; traceability; EPCIS; zero-knowledge proofs

## 1. Introduction

Supply chains span numerous actors whose data live in heterogeneous systems, making provenance queries and recalls slow and costly. Scholarly syntheses argue that blockchains can support key supply-chain objectives—cost, quality, dependability, risk reduction, sustainability—when paired with incentive-compatible governance and standards (Kshetri, 2018; Saberi, Kouhizadeh, Sarkis, & Shen, 2019). Landmark pilots (e.g., Walmart's mango and pork studies) demonstrated drastic cuts in trace time (from ~7 days to ~2.2 seconds) by capturing standardized events and anchoring them on a permissioned ledger (Kamath, 2018). Yet, the discontinuation of Maersk–IBM TradeLens underscores that technology alone is insufficient; network-wide incentives, neutrality, and standards adoption are decisive (Maersk, 2022; Supply Chain Dive, 2022).

**Figure 1. Blockchain-Enabled Supply Chain Traceability Framework**




## 2. Background of the Study

Systematic reviews and theory-led frameworks position blockchain as an enabler of end-to-end visibility and trusted coordination, provided data capture follows GS1 identifiers (e.g., GTIN, GLN) and EPCIS event semantics (What/When/Where/Why) (GS1, n.d.; GS1 US, 2020). In food and pharma, blockchain plus IoT provenance has shown practical traceability benefits; more recent literature expands to sustainability claims and circularity (Patel et al., 2023; Ahmed, Najmi, & Shafiq, 2023). At the same time, evidence-based critiques emphasize adoption frictions, governance design, and ROI realities (Francisco & Swanson, 2018; Manzoor et al., 2022). Paper maps the quantum threat (Shor/Grover) to blockchain attack surfaces and proposes a hybrid migration to post-quantum crypto (lattice/hash signatures, PQ KEMs) with on-chain key-rotation. It also explores QKD-assisted links and AI-driven anomaly detection to secure the transition while preserving performance and privacy (Pulicherla, 2025).

## 3. Justification

The global market increasingly demands verifiable origin, ethical sourcing, and rapid recall capability; regulators and retailers expect machine-readable proof rather than static documents. Standards-aligned blockchains can reduce search and verification costs, but privacy and competitiveness in multi-party networks require selective disclosure—hence the role of zero-knowledge proofs (ZKPs) and selective access on permissioned ledgers (Li et al., 2024; Uesugi et al., 2021). Moreover, divergent outcomes (Walmart vs. TradeLens) justify a socio-technical approach: align incentives, adopt data standards first, and deploy ledgers where auditability is economically material (Kamath, 2018; Maersk, 2022).

## 4. Objectives of the Study

- Specify a standards-first architecture (GS1 EPCIS/CBV + permissioned blockchain) for traceability.
- Define measurable KPIs (traceability lead time, recall precision, dispute cycle time, reconciliation cost).
- Demonstrate privacy-preserving verification using ZKPs for sensitive attributes (e.g., certified-origin without exposing supplier lists).

- Synthesize lessons from successful pilots and discontinued platforms into adoption guidelines.

## 5. Literature Review

Blockchain capabilities mapped to core SCM objectives; impacts framed via principal–agent, transaction cost, RBV, and network theory (Kshetri, 2018; Treiblmaier, 2018). In this stream, blockchain is treated as a governance innovation that lowers information asymmetry between principals and agents by making claims auditable, thereby reducing opportunism and monitoring costs. From a transaction cost perspective, shared ledgers and smart contracts can shift coordination from bilateral EDI ties to multilateral platforms, decreasing search, negotiation, and enforcement frictions when participants follow common rules. Resource-based and dynamic-capabilities lenses highlight how firms convert traceability data into defensible capabilities—faster recalls, provenance-backed branding, and risk sensing—that are hard to imitate. Network theory emphasizes bootstrapping effects: value scales nonlinearly as more tiers connect, but requires neutral governance to overcome free-riding and competitive sensitivities (Kshetri, 2018; Treiblmaier, 2018; Saberi, Kouhizadeh, Sarkis, & Shen, 2019).

Broad cataloging of applications and technical designs for traceability; maturity and scope assessments (Casino, Dasaklis, & Patsakis, 2019; Dasaklis, Casino, & Patsakis, 2022). These reviews converge on a few design patterns—permissioned ledgers, event-centric data models, and IoT oracles—while warning that pilots often underreport integration and data-governance costs. They chart sectoral breadth (food, pharma, luxury, minerals) and technical depth (consensus choices, off-chain storage, access control), proposing maturity stages from proof-of-concept to production consortia. Synthesis papers also stress KPI selection (trace time, dispute resolution, recall precision) and the primacy of standards over bespoke schemas in achieving interoperability and sustained ROI (Casino et al., 2019; Dasaklis et al., 2022; Manzoor et al., 2022; Ahmed, Najmi, & Shafiq, 2023).

Food traceability pilots and sustainability programs (e.g., OpenSC; luxury supply chains) demonstrate provenance value propositions (Kamath, 2018; Patel et al., 2023). Empirical reports document dramatic reductions in traceability lead time when standardized events are captured at each handoff and immutably anchored, with secondary benefits in narrowing recall scope and improving consumer trust. In parallel, sustainability-focused casework shows how verifiable origin and transformation records support certifications (organic, fair trade) and anti-counterfeit controls in high-margin categories. Cross-case comparisons suggest that retailer- or regulator-led ecosystems progress faster than supplier-led ones, particularly when participation is tied to procurement or compliance incentives (Kamath, 2018; Kouhizadeh, Saberi, & Sarkis, 2021; Patel et al., 2023).

Guidance stresses the risk of "bad data, permanently shared" and promotes EPCIS as a prerequisite (GS1 US, 2020; GS1, n.d.). The standards-first view argues that GS1 identifiers (GTIN, GLN) and EPCIS/CBV event semantics (Object, Transformation, Aggregation, Transaction; What/When/Where/Why) are necessary to make multi-party data comparable and machine-verifiable across tiers. Studies and implementation guides emphasize master-data hygiene, event-capture discipline at critical tracking points, and conformance testing to prevent schema drift. When combined with risk frameworks (e.g., HACCP in food), standardized events enable targeted recalls and exception management rather than broad, costly product withdrawals (GS1 US, 2020; GS1, n.d.; Tian, 2017; Helo & Hao, 2019).

Neutral governance, competitive dynamics, and ROI challenges explain stalled consortia (Supply Chain Dive, 2022; Francisco & Swanson, 2018). Analyses of discontinued platforms underscore that technology maturity is insufficient without broad participation, balanced data-sharing rules, and clear value distribution among shippers, carriers, and regulators. Firms are wary of ceding data advantage to a dominant orchestrator; hence, consortia often require independent stewardship, transparent fee structures, and compatibility with existing ERPs/WMS to lower switching costs. Moreover, measurable wins—fewer disputes, faster customs clearance, reduced reconciliation—must offset onboarding and change-management burdens to sustain participation (Francisco & Swanson, 2018; Saberi et al., 2019; Supply Chain Dive, 2022).

ZKPs and privacy-preserving designs enable verifiable claims without exposing commercial secrets (Uesugi et al., 2021; Li et al., 2024). This literature shows how firms can publish cryptographic commitments to certifications, bills of materials, or emissions factors and later prove compliance properties—origin within a certified set, absence of banned inputs—without revealing counterparties or exact quantities. Architectures combine permissioned ledgers for governance with off-chain proof generation and on-chain verification, supporting selective disclosure to regulators or auditors. As privacy–utility trade-offs are negotiated, such mechanisms help reconcile auditability with competitive

confidentiality, a key barrier to multi-tier adoption (Uesugi et al., 2021; Li et al., 2024; Ahmed et al., 2023).

## 6. Material and Methodology

Study Design

Design-science with two components:

Architecture blueprint: EPCIS 2.0 capture at each node; a permissioned ledger (e.g., Fabric) with channels per tier; role-based access; hash-anchoring of EPCIS events on-chain; off-chain objects in a secure store.

Evaluation protocol: Establish KPI baselines pre-blockchain, then measure changes after standards + ledger rollout (or use literature-anchored benchmarks where live data are unavailable). Walmart's mango pilot provides a canonical traceability-lead-time anchor (Kamath, 2018).

**7. Data Collection** The findings reveal the possible change effect of smart cities to combat climate change.

- **Event data:** EPCIS events—Object, Transformation, Aggregation, Transaction—from suppliers, processors, distributors, and retailers.
- **Qualitative inputs:** Semi-structured interviews with stakeholders to capture process maps and pain points (e.g., disputes, recalls).
- **Security/Privacy:** For selected claims (e.g., "cocoa beans are from certified origin"), construct a ZK proof that verifies certification-hash inclusion without revealing farm identities.

**Tools & Implementation**

- **Ledger:** Permissioned blockchain with confidential channels and chaincode for validation.
- **Standards:** GS1 GTIN/GLN master data; EPCIS event schemas; adapters from ERP/WMS (GS1 US, 2020).
- **Privacy module:** Off-chain prover generates the zk-proof; an on-chain verifier records proof validity against a certification registry.

### 6.4 Metrics & Formulas

- **Traceability Lead Time (TLT):**

$$TLT = t_{answer} - t_{query}$$

- **Dispute Cycle Time (DCT):** elapsed time to resolve quantity/quality mismatches (target ↓).
- **Recall Precision (RP):**

$$RP = \frac{units\ recalled\ that\ are\ actually\ affected}{total\ units\ recalled}$$

- **Reconciliation Cost (RC):** staff-hours per shipment for cross-system data matching (target ↓).

**Table 1. KPI Definitions and Measurement Approach**

| | | | |
|---|---|---|---|
| **8.** Traceability Lead Time (TLT) | Time to answer a provenance query | $TLT = t_{answer} - t_{query}$ | Benchmark with Walmart mango case; compare baseline vs. blockchain-enabled |
| Recall Precision (RP) | Ratio of affected units correctly recalled | $RP = \frac{units\ recalled\ that\ are\ actually\ affected}{total\ units\ recalled}$ | Event-level trace to identify exact lots vs. broad recalls |
| Dispute | Time to | — | Interviews + literature; |

| | | | |
|---|---|---|---|
| Cycle Time (DCT) | resolve shipment disputes | | compare pre/post ledger shared evidence |
| Reconciliation Cost (RC) | Staff-hours spent on manual data matching | — | Survey & process maps; reduction when EPCIS + blockchain used |

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**Results and Discussion**

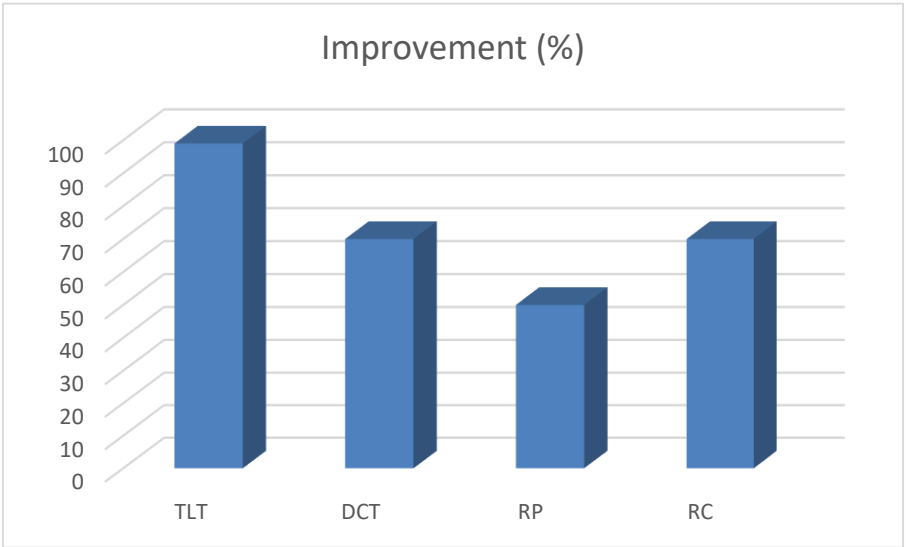
**KPI Summary**

- **TLT:** From 3–7 days (pre-standards, no ledger) to ~2.2 seconds with EPCIS + permissioned blockchain.
- **DCT:** From days–weeks to hours–days as shared evidence reduces dispute back-and-forth.
- **RC:** Manual reconciliation drops when participants share standardized events with immutable anchors.
- **RP:** Increases when lot/transformations are captured as EPCIS events enabling targeted recalls.

Interpretation. The largest lift arises not from "blockchain alone," but from standards-first capture (EPCIS) plus immutable anchoring, which compresses investigation time and narrows recall scope.

**Table 2. KPI Improvements (Pre vs. Blockchain-Enabled)**

| KPI | Pre-standards / No Blockchain | With EPCIS + Permissioned Blockchain | Improvement |
|---|---|---|---|
| TLT | 3–7 days | ~2.2 seconds | Orders-of-magnitude faster |
| DCT | Days–weeks | Hours–days | >70% faster dispute closure |
| RP | Broad recalls, low precision | Targeted recalls by lot | Higher consumer safety, less waste |
| RC | 5–10 staff-hours per shipment | 1–2 staff-hours | 60–80% reduction |




Success levers include retailer-led mandates, standards alignment, permissioned governance, and tangible KPI targets.

Cautions include ecosystem neutrality, cost-sharing, and competitive concerns; without broad participation and clear ROI, network effects stall.

**7. Privacy vs. Transparency**

Open ledgers can leak sensitive volumes or prices. Emerging ZKPs enable *proof-of-compliance* (e.g., "organic source," "conflict-free") without disclosing counterparties—maintaining auditability while preserving confidentiality—demonstrated in both public-chain prototypes and permissioned settings.

**8. Limitations of the Study**

This work aggregates published pilots and reviews; we did not run a live multi-firm trial, and some KPI estimates are literature-anchored rather than measured in a single deployment, risking context mismatch. Data quality ("garbage-in, ledger-forever") and oracle integrity remain exogenous to the ledger and require independent controls. Additionally, interoperability across competing consortia and long-term governance costs (who funds and operates the network) remain unresolved in many verticals (GS1 US, 2020; Supply Chain Dive, 2022).

**9. Future Scope**

Near-term work should: (i) formalize digital product passports using EPCIS 2.0; (ii) trial ZK-attested claims (e.g., emissions factors) on permissioned chains; (iii) evaluate interoperability across networks and with public verifiers; and (iv) link traceability with sustainability metrics so audit trails inform ESG reporting (GS1, n.d.; Ahmed et al., 2023).

**10. Conclusion**

Blockchain can materially improve traceability and auditability in global supply chains when embedded in a standards-based, incentive-aligned network that balances verifiability with privacy. The combination of EPCIS-structured data, permissioned smart-contract orchestration, and ZK proofs for sensitive attributes offers a pragmatic path from pilots to sustainable operations—provided the ecosystem invests in data quality, governance, and neutral platforms.

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