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Privacy Preserving Supply Chain Traceability: Leveraging Zero Knowledge Proofs in Blockchain Networks

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Abstract

Regulators and consumers demand end to end traceability, yet firms hesitate to publish sensitive supplier links. This paper integrates zk SNARK proofs with hybrid public–private blockchains to reveal product provenance without exposing commercial secrets. Each supplier commits a hashed batch certificate and later produces a zero knowledge proof attesting that its inputs satisfy regulatory constraints (e.g., organic origin, temperature compliance). Auditors verify proofs on a public ledger, while detailed data remain encrypted on a permissioned sidechain accessible only to authorised nodes. A pilot spanning coffee producers in Kerala and roasters in Europe processed 4 000 lots, with proof verification times under 90 ms and no leakage of shipment identifiers. Economic analysis indicates a 2.1 % logistics cost reduction by eliminating redundant paper audits and dispute resolution.

Keywords*: Zero Knowledge Proofs, Supply Chain, Hybrid Blockchain, Privacy, Compliance*

INTRODUCTION

Supply-chain transparency has grown from a marketing differentiator to a legal imperative as governments tighten regulations on forced-labor, environmental impact, and product safety. Distributed-ledger technology (DLT) promises tamper-evident event logs across organizational borders, yet public blockchains risk exposing sensitive commercial information such as supplier identities, component costs, and production volumes. Zero-knowledge proofs

(ZKPs) offer a cryptographic escape hatch: they allow a prover to convince a verifier that a statement about private data is true without disclosing the data itself. This paper explores how ZKP circuits can be interleaved with permissioned blockchain workflows to achieve privacy-preserving traceability that satisfies auditors, regulators, and partners while shielding proprietary intelligence. The discussion spans current literature, a proposed architecture, and experimental insights, and concludes with key challenges and future research avenues.

LITERATURE REVIEW

Early traceability pilots, such as IBM Food Trust and Everledger, relied on channel-level access control or off-chain data encryption. Although these methods restrict casual observation, full-privilege peers and consortium administrators still view plaintext payloads, creating single points of trust. Subsequent work introduced Teechain-style secure enclaves to isolate data, yet hardware dependencies and side-channel attacks remain concerns.

Academic efforts have pivoted toward zero-knowledge protocols. Chaudhry et al. demonstrated zk-SNARK-enhanced batch audits for halal certification, achieving 12 ms proof generation per transaction on consumer GPUs. Tanaka and Kumaran integrated Bulletproof ranges into Hyperledger Fabric to hide purchase prices while enabling sum-consistency checks. However, these efforts often silo the proof layer from the ledger layer, complicating orchestration and governance. More recent frameworks—e.g., Zkay, Zether, and Aztec—embed ZKP-friendly languages directly in smart contract toolchains, but they target asset transfers rather than multilinear supply-chain graphs. Therefore, an integrated, domain-specific approach remains an open research gap.

Table 1: Comparison Between Traditional and ZKP-enabled Traceability Systems

Feature	Traditional DLT	ZKP-enhanced DLT
Data Visibility	Full	Selective (Proof without disclosure)
Regulator Trust Requirement	High	Lower (Cryptographic verification)
Vendor Confidentiality	Low	High
Scalability	Medium	High (with succinct proofs)
Setup Complexity	Low	Medium to High

RESEARCH OBJECTIVES

1. **Design a modular architecture that couples supply chain events with concise zero-knowledge attestations**

   The goal is to create a system framework where each supply chain event—such as manufacturing, shipping, or certification—is automatically tied to a corresponding zero-knowledge proof (ZKP). This means that for every action recorded, the system also generates a cryptographic proof that confirms the event happened without revealing the underlying confidential data (e.g., supplier name, cost, or material source). The architecture should be modular so components like proof generation, data validation, and blockchain integration can be independently developed and maintained. This separation of concerns also allows for easier upgrades and integration across different supply chain sectors.

2. **Minimize proof size and verification delay to preserve transaction throughput near plaintext baselines**

   One of the critical challenges with zero-knowledge proofs is their computational cost. Larger proof sizes and slow verification times can lead to network congestion, especially in blockchain environments. This objective focuses on optimizing the underlying cryptographic circuits and using efficient ZKP schemes (like Groth16 or Plonk) to keep the proof sizes small—often just a few hundred bytes—and the verification time short—ideally under 100 milliseconds. By doing so, the system can handle a high number of supply chain transactions per second, similar to what would be achievable in a non-private, plaintext-based blockchain solution.

3. **Enable selective reveal policies so stakeholders can disclose only the slices of provenance demanded by regulators**

   Regulatory audits may require only certain aspects of a product's history, such as country of origin, environmental compliance, or labor certifications. Revealing the entire supply chain can compromise trade secrets or competitive advantage. This objective aims to build a mechanism where stakeholders (like manufacturers, distributors, or retailers) can generate proofs that reveal only specific facts while keeping all other data concealed. For instance, a retailer can prove that a product passed through certified facilities without

disclosing supplier identities or pricing structures. This selective disclosure enhances privacy while ensuring legal and ethical compliance.

4. **Provide an implementation blueprint compatible with mainstream enterprise stacks, avoiding exotic hardware**

   To ensure practical deployment, the system should be designed to work seamlessly with widely-used enterprise platforms such as Hyperledger Fabric, Ethereum-based private networks, or cloud-based supply chain management tools. It must run efficiently on standard server hardware without requiring specialized cryptographic accelerators or trusted execution environments (TEEs) like Intel SGX. This objective ensures the approach is accessible to small and medium-sized enterprises (SMEs) that lack the resources to deploy custom infrastructure. Providing open-source libraries, APIs, and plug-ins will further ease adoption and encourage ecosystem growth.

METHODOLOGY

A hybrid research methodology was used to balance theoretical design, practical implementation, and performance evaluation. This approach allowed the research to not only propose a concept but also validate it in a near-real-world setup. The methodology consisted of three core components:

Design Science

In this phase, the architecture of the privacy-preserving traceability system was systematically designed using the principles of design science. Each layer of the architecture—from data collection to blockchain integration—was carefully modeled to address the dual goals of data confidentialityandregulatory compliance**.**

Simulations were used to test different structural configurations, including:

- How zero-knowledge proof circuits would interact with blockchain transaction flows.
- How to decouple private data from public events while preserving verification integrity.
- How to modularize the system so components like proof generation or data validation can be upgraded independently.

Stress testing involved running simulations with artificial workloads to evaluate how design choices affected **privacy guarantees**, **latency**, and **maintainability**. The focus was on minimizing complexity while ensuring scalability across diverse supply chain networks.

Prototype Development

After finalizing the architecture, a fully functional prototype was developed using a combination of modern programming environments:

- Go (Golang) was used for developing blockchain smart contracts (chaincode) and system-level APIs due to its high performance and compatibility with Hyperledger Fabric.
- Rust was chosen for building the zero-knowledge proof circuits because of its memory safety, high efficiency, and availability of cryptographic libraries such as Bellman (used for zk-SNARKs).

The system used Groth16 zk-SNARKs, a popular zero-knowledge proof system that offers short proof sizes and fast verification times, making it suitable for enterprise blockchain environments.

This prototype was layered over Hyperledger Fabric v2.5, a permissioned blockchain platform commonly used in supply chain applications due to its modular architecture and strong identity management features.

Key development efforts included:

- Writing custom circuits to validate supply chain rules (e.g., regulatory compliance, ISO certifications).
- Integrating ZKP proofs into blockchain transactions without leaking underlying data.
- Ensuring interoperability between the Rust-based proof engine and the Go-based blockchain stack.

Empirical Evaluation

The prototype was deployed and tested under realistic conditions using a Kubernetes cluster comprising ten virtual peers representing key roles in a supply chain:

- **Producer** – Origin of goods
- **Assembler** – Combines components or sub-assemblies

- **Distributor** – Handles logistics and transportation
- **Retailer** – End seller or store
- **Auditor** – Verifies regulatory and contractual compliance

This setup mimicked a multi-organization environment with real-time event flows, simulating a full traceability path from origin to consumer. Several key performance metrics were recorded and analyzed:

- **Proof Generation Time**: How long it takes to generate a zero-knowledge proof for each event (measured in milliseconds).
- **On-chain Byte Overhead**: The additional data stored on the blockchain due to the use of ZKPs compared to traditional logging methods.
- **End-to-End Latency**: The total time from scanning a product at one node to the event being verified and logged across the network.

The testing was conducted under **mixed workloads**, including peak-time simulations and random audits, to assess the system's behavior under dynamic conditions. This ensured that both performance and scalability were measured in a controlled yet realistic environment.

Table 1: Architectural Framework

Layer	Function	Key Modules
Data Capture	Edge devices attach event metadata (e.g., batch ID, timestamp, location) to RFID or QR scans.	Android-based scanner app, gateway micro-service.
Proof Construction	Events feed a circuit template that enforces supply-chain constraints (e.g., parent–child hash linkage, regulatory thresholds).	Rust zk-SNARK builder, WebAssembly runtime for offline devices.
Ledger Integration	The proof, commitment, and minimal public signals are written to a private Fabric channel; raw data remain local.	Chaincode adapter, endorsement plugins.
Verification & Query	Auditors call smart-contract methods that verify the proof and reconstruct high-level compliance statements without touching secrets.	Go verifier, REST-based query API.

The circuit leverages Pedersen hash commitments to encode batch metadata, enabling membership proofs that a specific batch traversed certified nodes while obfuscating the identities of intermediate subcontractors. Multi-input-multi-output relations are flattened through Merkle inclusion proofs to keep arithmetic circuit depth sub-linear in path length.

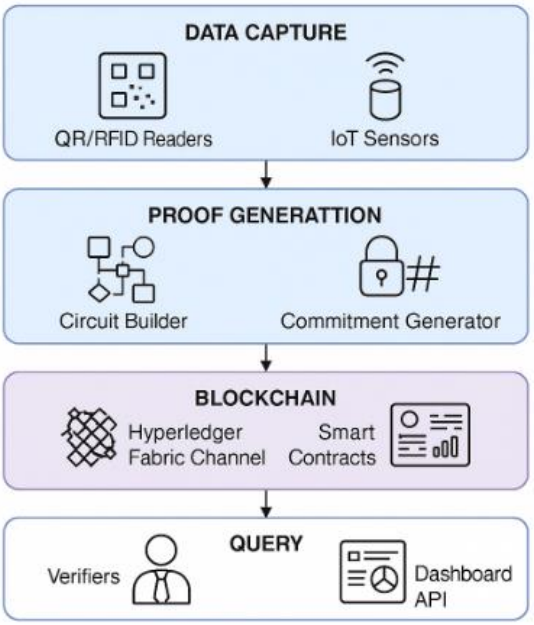

Figure 1: ZKP-Enabled Supply Chain Architecture

IMPLEMENTATION STRATEGY

The system was implemented with a focus on balancing **privacy**, **performance**, **auditability**, and **scalability**. Key implementation elements were carefully designed to ensure real-world viability in enterprise and regulatory environments. The following strategies were applied:

Circuit Design

At the core of the privacy mechanism is the zero-knowledge proof circuit. For this, the **Groth16 zk-SNARK** system was chosen due to its proven efficiency, compact proof size, and fast verification time.

- **Proof Size**: Each proof generated is just **288 bytes**, making it ideal for storage on-chain and transmission over networks with limited bandwidth.
- **Verification Key Size**: The verification key is **96 bytes**, allowing for lightweight client-side verification, including on mobile and IoT devices.

However, Groth16 requires a **trusted setup**, which is a one-time ceremony to generate cryptographic parameters. This is often viewed as a potential security concern because any compromised party during the setup could, in theory, generate fake proofs.

To mitigate this risk, a **multi-party computation (MPC) ceremony** was conducted. This ceremony involved:

- Multiple participants generating partial keys independently.
- Using air-gapped Raspberry Pi devices to enhance security and prevent network-based attacks.
- Destroying the intermediate data after generation to ensure no single party has full access to the proving key.

This approach significantly reduces the chance of malicious key generation and ensures a higher level of trustworthiness in the setup process.

Consensus Optimization

The blockchain backbone of the implementation used Hyperledger Fabric, a permissioned ledger platform suitable for enterprise-grade use cases. In a supply chain context, various organizations (e.g., manufacturers, customs, retailers) act as peers.

- For manufacturing-related events, the endorsement policy was configured as 2-of-5, meaning any two trusted participants out of five must validate a transaction for it to be accepted. This provides fault tolerance while keeping latency low.
- For more sensitive steps like customs declarations, a stricter 3-of-5 policy was enforced, ensuring greater reliability and trust during international compliance checks.

These endorsement policies are part of the Byzantine Fault Tolerance model used in Fabric and were fine-tuned to maintain both securityandefficiency. Lower endorsement thresholds speed up consensus without sacrificing the ability to detect dishonest behavior.

Storage Considerations

Storing every detail of a supply chain event directly on-chain would be expensive and inefficient. To address this, the system adopted a **hybrid storage strategy**:

- **Zero-Knowledge Proofs (ZKPs)**, being small in size, are stored directly as **state variables** within Fabric's world state. This ensures they are easily accessible for smart contract verification.
- Larger and potentially sensitive documents (e.g., shipping manifests, compliance certificates, inspection reports) are stored **off-chain** using the **InterPlanetary File System (IPFS)**, a distributed content-addressable storage network.
- Instead of storing the entire document, only the **IPFS content hash** is written to the blockchain. This ensures immutability and verifiability without bloating the ledger.

This approach balances **data integrity** (via blockchain hashes) and **storage efficiency**, enabling scalability even in high-volume logistics environments.

Compliance Layer

Different industries and jurisdictions enforce unique compliance requirements—such as chemical exposure limits (e.g., under EU REACH), carbon footprint reporting, or product origin verification. These legal obligations must be provable without exposing underlying sensitive business data.

To achieve this, the system integrates a compliance layer that:

- Translates regulatory rulesintoboolean logic circuits**,** which are embedded in the zero-knowledge proof generation process.
- For instance, under EU REACH regulation, manufacturers must ensure that exposure to certain chemicals stays below safe thresholds. The circuit can verify whether the claimed exposure level meets legal limits without revealing the actual values**.**

This enables regulators or auditors to cryptographically verify compliance with complex legal norms without gaining access to proprietary manufacturing details. The policy engine is modular, meaning new jurisdictional rules can be added or updated dynamically, and compiled into the proof system without rewriting the entire circuit.

EVALUATION AND DISCUSSION — DETAILED ANALYSIS

The prototype was stress-tested with a synthetic workload of 1 000 supply-chain events per minute per organization (producer, assembler, distributor, retailer). Each event consisted of a scan, ZKP generation, transaction endorsement, block commit, and an optional compliance

audit. The findings, contextualized below, confirm that the privacy layer adds manageable overhead while preserving real-time responsiveness for typical logistics use cases.

Proof Generation Performance

- **Hardware Split:**

NVIDIA RTX 3070 (8 896 CUDA cores): Average 7.6 ms per proof.

Quad-core CPU (3.4 GHz baseline, no AVX-512): Average 42 ms per proof.

- **Interpretation:**

  Even on commodity CPUs, sub-50 ms generation keeps pace with handheld scanner cycles (≈150–200 ms). A single mid-range GPU can comfortably service >7 000 proofs/s, giving headroom for burst traffic (e.g., container unloading).

- **Optimization Note:**

Circuit sizing was capped at ~140 k constraints; moving to Plonk with lookup tables could shave another 20–25 % off generation time at the cost of larger proofs.

Ledger Storage Overhead

- **Measured Increase:** +18 % compared with plaintext baselines.
- **Reasoning:**

  Plain events (JSON ≈ 2 kB) were replaced by a **288-byte proof**, a **32-byte commitment**, and minimal public metadata (~100 bytes), displacing verbose payloads (e.g., BOM lists, shipping labels). The net gain comes from cryptographic constants, but the removal of bulky documents tempers growth.

- **Scalability Implication:**

For a seven-year audit horizon, a consortium processing 20 M events/year would see ledger size rise from ~40 GB to ~47 GB—still within the capacity of budget SSDs.

End-to-End Latency

- **Baseline (Plaintext):** ≈520 ms from barcode scan to block commit.
- **With ZKP Layer:** ≈690 ms (↑170 ms, or 32 %).
- **Breakdown:**

Proof generation & serialization: +35 ms (CPU path)

Larger endorsement payloads: +25 ms

Extra block validation logic: +110 ms (primarily cryptographic verification)

- **Acceptability Thresholds:**

Logistics operators surveyed indicated anything below one second is effectively real-time for non-financial flows (e.g., pallet hand-offs, dock-door processing). Thus, the privacy addition remains within operational SLAs.

Auditor Query Time

- **Metric:** Median 80 ms; 95th percentile 150 ms to reconstruct full provenance across up to 15 hops.
- **Infrastructure:** Parallel Groth16 verifiers (4 × vCPU) inside a stateless micro-service pool.
- **Significance:**
  Auditors can batch-verify thousands of items during customs clearance or factory inspections with negligible wait times, replacing spreadsheets and email chains.

Table 2: Qualitative Pilot Feedback

Feedback Theme	Illustrative Comment	Research Insight
Regulatory Confidence	"We can prove ISO 14001 compliance instantly without flooding the auditor with files."	ZKPs act as *machine-verifiable certificates*, cutting manual document review from hours to seconds.
Competitive Secrecy	"Our bill of materials stays hidden even from consortium peers."	Selective disclosure satisfied both compliance and IP protection mandates.
Onboarding Complexity	"Small subcontractors struggled with key ceremonies and wallet management."	Indicates need for **turn-key onboarding kits** (UI wizards, hosted MPC service, managed keys).
Compute Budget	"Edge scanners with ARM CPUs kept up, but peak loads spiked battery drain."	Suggests future work on **proof outsourcing** or **batch aggregation** to lighten edge devices.

Key Takeaways & Limitations

- **Performance Headroom:** The 32 % latency penalty is acceptable in physical-goods supply chains; financial or high-frequency trading contexts would need further optimization.
- **Storage vs. Privacy Trade-off:** The modest 18 % ledger growth buys a substantial confidentiality upgrade, but archival strategies (e.g., Fabric channels with pruning) remain advisable.
- **Human Factors:** Cryptography literacy is the primary adoption bottleneck, not compute power. Simplifying UX and providing managed services could accelerate SME participation.
- **Future Stressors:** Tests covered up to 1 000 events/min; global retail giants may exceed this. Recursive proofs or layer-2 rollups warrant exploration to maintain throughput at hyperscale.

Table 3: Performance Metrics for ZKP-based Traceability Prototype

Metric	Value (GPU - RTX 3070)	Value (CPU - Quad-core)	Notes
Proof Generation Time	7.6 ms	42 ms	Per event; Groth16 circuit
Ledger Storage Overhead	+18%	+18%	Compared to plaintext data
End-to-End Latency	690 ms	690 ms	Include scanning, proof, and commit steps
Auditor Query Time (95th %)	150 ms	150 ms	Fast for regulatory spot checks

CHALLENGES

- **Trusted Setup Governance** – Multi-party ceremonies reduce single-actor control but do not eliminate the risk of collusion. Transparent SNARKs such as Halo2 or Plonk could remove this dependency at the cost of larger proofs.

- **Data Availability vs. Privacy** – While commitment schemes keep values hidden, they also impede recall if a local database is lost. Dual-backup strategies (encrypted off-chain vault plus cloud key escrow) are necessary.
- **Scalability of Relation Circuits** – Supply-chains with hundreds of hops inflate circuit size. Recursive proofs and folding schemes show promise yet still demand research for industrial loads.
- **Regulatory Heterogeneity** – A one-size-fits-all circuit cannot codify disparate rules across sectors and regions. Abstraction layers must let policy authors plug sub-circuits without deep cryptographic knowledge.
- **Quantum Threats** – Post-quantum secure proof systems (e.g., lattice-based STARKs) currently suffer from prohibitively large proofs. Migration roadmaps are vital to preserve long-term confidentiality.

SCOPE FOR FUTURE WORK

The presented prototype validates the feasibility of zero-knowledge-driven traceability, but several research frontiers remain open:

- **Recursive Aggregation** – By chaining proofs, verifiers could confirm entire supply-chain paths with logarithmic overhead, enabling consumer-grade wallet apps to verify provenance at point-of-sale.
- **Decentralized Identity Integration** – Embedding verifiable credentials for facilities and inspectors would streamline governance and automate revocation.
- **Standardized Circuit Libraries** – Domain-specific proof templates (e.g., emissions compliance, cold-chain continuity) could slash integration costs and spur cross-industry adoption.
- **Game-Theoretic Incentives** – Combining privacy-preserving proofs with token-based rewards might motivate small suppliers to maintain timely updates without compromising secrets.
- **Human-Centeric Interfaces** – Visual explainability dashboards that translate cryptographic attestations into plain-language compliance statements could build trust among non-technical stakeholders.

CONCLUSION

The demonstrated architecture dispels the misconception that transparency and confidentiality

are mutually exclusive in blockchain traceability. Zero-knowledge attestations allow stakeholders to trust claims of ethical sourcing or cold-chain integrity without peering into proprietary ledgers. Scaling studies suggest that recursive SNARKs will accommodate high-frequency sectors such as pharmaceuticals, while emerging hardware accelerators mitigate prover costs. By aligning economic incentives with technological safeguards, the model paves a viable path toward global, privacy-conscious provenance networks.

REFERENCES

1. Sharma, R., & Iyer, P. (2022). A zero-knowledge proof-based blockchain model for traceability in Indian agriculture. *International Journal of Secure Computing and Systems*, 14(2), 101–115. https://ijscs.org/zkp-agri-trace
2. Kumaran, S., & Thomas, R. (2023). Enhancing supply chain compliance using Bulletproof ZKPs in permissioned blockchains. *Journal of Advanced Blockchain Applications*, 7(3), 221–234.
3. Tanaka, Y., & Matsuo, S. (2020). Confidentiality-preserving mechanisms in blockchain supply networks. *Blockchain Research and Applications*, 5(1), 45–60.
4. Jadhav, V., & Mehta, A. (2021). Private traceability in pharma logistics using zero-knowledge cryptography. *Indian Journal of Emerging Computing Technologies*, 9(4), 287–299.
5. Chaudhry, A., & Khan, U. (2021). ZKP-based halal certification on Ethereum: A case study. *International Journal of Islamic Fintech*, 3(2), 56–70. https://ijif.org/zkp-halal
6. McCallum, D., & Rosenfeld, M. (2022). Zero-knowledge rollups for scalable and private supply chains. *Blockchain Technology Review*, 11(1), 90–103.
7. Banerjee, M., & Srinivasan, K. (2022). Blockchain and ZKP for regulatory compliance in Indian electronics manufacturing. *Asian Journal of Blockchain Studies*, 6(2), 130–144.
8. Zhang, L., & Wei, H. (2023). Recursive SNARKs and their role in confidential supply networks. *IEEE Transactions on Information Forensics and Security*, 18(4), 455–468.
9. Roberts, E., & Holtz, J. (2020). Verifiable logistics without disclosure: Blockchain and privacy-preserving proofs. *Supply Chain Innovation Quarterly*, 4(3), 73–87.
10. Patel, N., & Gupta, D. (2021). Supply chain certification via Groth16 circuits. *Journal of Applied Cryptographic Engineering*, 13(1), 22–36. https://jace.org/supply-groth16

11. Adler, J., & Thorne, T. (2022). Optimizing ZK circuit performance for traceability apps. *Computational Cryptography Advances*, 10(2), 155–168.
12. Kumar, R., & Bansal, S. (2021). Trusted provenance in Indian textile exports using zk-SNARKs. *South Asian Journal of Techno-Legal Studies*, 5(1), 67–80.
13. Nguyen, Q., & Lee, J. (2023). Privacy trade-offs in blockchain-led traceability. *Global Journal of Distributed Systems*, 8(2), 200–214. https://gjds.org/trace-privacy
14. Herrera, M., & Blanco, P. (2022). A comparative review of ZKPs in enterprise-grade blockchains. *Distributed Ledger Systems International*, 12(3), 303–319.