TraceDAG

1. Executive Summary

TraceDAG is a blockchain-enabled platform that transforms supply-chain transparency by attaching a unique digital identity to every product or batch in the form of a non-fungible token (NFT). Each transfer of custody is written immutably to a BlockDAG blockchain, allowing manufacturers, logistics partners, and consumers to audit a product's journey from origin to purchase with a single QR scan. The solution mitigates counterfeiting, streamlines recalls, and unlocks new financial utilities such as asset-backed lending.

2. Introduction

Global commerce relies on complex, multi-party supply chains that often lack a shared, trustworthy record of events. Paper-based trails and isolated databases expose manufacturers and buyers to fraud, grey-market diversion, and inefficient dispute resolution. TraceDAG leverages decentralized ledger technology to create an open and verifiable log of every checkpoint a product encounters, fostering trust where traditional systems fall short.

3. Problem Statement

- **Counterfeit Goods:** High-value and regulated products are frequently duplicated or tampered with, costing industries billions annually.
- **Data Silos:** Each party in the chain maintains proprietary records, preventing end-to-end visibility.
- **Consumer Mistrust:** Shoppers lack an easy way to confirm a product's authenticity, origin, or ethical compliance.
- **Manual Reconciliation:** Recall procedures and audit trails are slow, error-prone, and costly.

4. Objective

TraceDAG's primary objective is to establish a tamper-proof, real-time, and user-friendly system for capturing and sharing supply-chain events. The platform seeks to:

1. Digitally represent every manufactured item or batch as an NFT containing essential metadata.
2. Record each hand-off—factory, distributor, warehouse, retailer—directly on a BlockDAG ledger.
3. Provide a single QR interface for any stakeholder to verify the full chain of custody.
4. Abstract blockchain complexity through gasless interactions and smart-account wallets.

5. Methodology

5.1 Digital Representation

At production time, the manufacturer mints an NFT containing the product's SKU, batch number, manufacture date, and a cryptographic hash of any supporting certificates. The minting transaction also stores an IPFS content identifier (CID) that links to an off-chain JSON package with extended metadata.

5.2 Checkpoint Logging

Every participant in the logistics network uses a web or progressive-web application (PWA) to scan the product's QR code. The app signs a meta-transaction that appends a new checkpoint struct to the NFT's on-chain data. The struct contains:

- **Timestamp (block + local)**
- **GPS coordinates / location label**
- **Handler ID (wallet address)**
- **Optional note or document CID**

5.3 Off-chain Document Storage

Invoices, quality certificates, and customs forms are stored on IPFS or Arweave for cost-effective permanence. CIDs are referenced in the NFT to give auditors instant access without bloating on-chain storage.

5.4 Consumer Verification

A public “Product View” page renders a timeline or interactive map of the NFT’s checkpoints. If all events satisfy the schema and pass signature validation, the interface displays an **Authentic** badge in green. Any anomalies trigger a warning banner.

6. System Architecture

Layer	Component	Responsibility
Frontend	React + Vite PWA	QR scanning, dashboards, public viewer
State	Zustand	Client-side cache, session handling
Blockchain	Solidity contracts on a BlockDAG chain	Minting, checkpoint append, role enforcement
Relayer	Biconomy / custom service	Gas abstraction, meta-tx signing
Indexing	The Graph / QuickNode Streams	Real-time data feeds for UI
Storage	IPFS / Arweave	Off-chain files, metadata JSON

6.1 Smart Contracts

- **ProductToken.sol** – ERC-721-compatible contract that mints tokens and exposes appendCheckpoint().
- **RoleManager.sol** – Maintains manufacturer, logistics, and auditor roles.
- **MetaTxForwarder.sol** – Verifies EIP-2771 meta-transactions for gasless UX.

6.2 Frontend Flow

1. User signs in with Web3Modal (smart account).
2. Manufacturer dashboard calls mintProduct() via relayer.
3. QR code generated locally using token ID + checksum.
4. Scanner view decodes QR → sends appendCheckpoint() meta-tx.
5. UI listens to contract events, updates timeline.

7. Feature Set

7.1 Core Features

- **Mint & Tag Products**
- **Checkpoint Scanner**
- **Customer Verification Page**
- **Document Attachment via IPFS**
- **Role-based Access Control**

7.2 Nice-to-Have Enhancements

- Carbon footprint calculator (distance × emission factors)
- AI anomaly alerts (skipped or out-of-order checkpoints)
- DeFi lending module using product NFTs as collateral

8. Technology Stack

- **Frontend:** React 18, TypeScript, TailwindCSS, Vite
- **State Management:** Zustand
- **Web3:** Ethers.js, Wagmi, Web3Modal
- **Blockchain:** Solidity 0.8.x on BlockDAG-compatible EVM
- **Storage:** IPFS / Arweave
- **Testing:** Vitest, Hardhat, Playwright
- **CI/CD:** GitHub Actions → Netlify

9. Implementation Details

9.1 Smart Contract Design Principles

- Use of struct Checkpoint with indexed events for efficient off-chain queries.
- EIP-712 typed data signing to reduce replay attacks.
- Upgradeability via UUPS proxy for future feature additions.

9.2 Frontend Considerations

- Camera access handled with @zxing/browser for robust QR scanning.
- Offline mode caches the product timeline via service workers.
- Dark-mode and WCAG 2.1 AA color contrast support.

10. Testing and Validation

- **Unit Tests:** Solidity functions covered by Hardhat + Chai.
- **Integration Tests:** Simulated checkpoint flows in a local Ganache fork.
- **E2E Tests:** Playwright scripts validate mint-to-verify user journey.
- **User Testing:** Warehouse staff performed 20 mock scans with 100 % success rate.

11. Potential Challenges & Mitigations

Challenge	**Mitigation**
High on-chain fees	Batch writes hourly, compress data, or migrate to an L2 rollup
Bad data entry	Multi-sig validation, IoT sensor fusion in future releases
User resistance to Web3 wallets	Smart-account abstraction, email + OTP onboarding

12. Future Roadmap

1. **Quarter 1 – 2026:** Deploy to public testnet, integrate carbon tracker.
2. **Quarter 2 – 2026:** Launch AI anomaly engine, finalize DeFi lending prototype.
3. **Quarter 3 – 2026:** Pilot with two FMCG brands, collect field feedback.
4. **Quarter 4 – 2026:** Production rollout, seek Series A funding.

13. Business Impact & Benefits

- **Revenue Protection:** Brands reduce counterfeit loss and grey-market diversion.
- **Consumer Trust:** Shoppers verify authenticity in seconds, boosting brand loyalty.
- **Regulatory Compliance:** Immutable logs simplify recalls and audits.
- **New Revenue Streams:** Tokenized products enable asset-backed financing.

14. Sustainability & ESG Considerations

By offering a carbon tracking module and enforcing transparent sourcing documentation, TraceDAG supports companies in meeting ESG reporting requirements and driving greener logistics decisions.

15. Conclusion

TraceDAG delivers a practical, user-centric approach to supply-chain traceability powered by blockchain. The platform not only addresses immediate concerns around counterfeiting and transparency but also lays the groundwork for innovative financial services linked to real-world assets. With a clear roadmap and scalable architecture, TraceDAG is positioned to become a cornerstone in the next generation of trustworthy global commerce.