

**AI-ENABLED BLOCKCHAIN TRACEABILITY FOR MILK SUPPLY**

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**Abstract:**

India's decentralized milk supply chain continues to face critical challenges, including adulteration, unauthorized container access, and undocumented handling—issues exacerbated by limited digital infrastructure in rural regions. Existing traceability mechanisms, such as QR codes and cloud-dependent platforms, lack tamper-evidence, are easily duplicated, and perform poorly in offline environments. This study proposes a blockchain-enabled, NFC based smart lid system designed to establish secure, low-cost, and tamper-evident traceability tailored to these constraints. Enhance the system's intelligence and responsiveness, we integrate artificial intelligence across key functions: tamper prediction and detection, anomaly monitoring, fraud prevention, route optimization, demand forecasting, and predictive maintenance. These capabilities enable initiative-taking risk mitigation, data-driven logistics, and improved operational reliability, while maintaining compatibility with intermittent connectivity. By combining AI-driven insights with blockchain-backed immutability, the proposed solution delivers scalable, verifiable, and offline-capable traceability—supporting greater transparency, efficiency, and trust across India's rural dairy network.

**Keywords:** Blockchain Traceability, NFC Smart Packaging, Tamper Detection, Anomaly Detection, Route Optimization, Predictive Maintenance, Demand Forecasting, Supply Chain AI, Chain-of-Custody Verification.

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**Introduction:**

India's milk supply chain is one of the largest in the world, involving millions of farmers, cooperatives, transporters, and distributors. Despite its vast scale and economic importance, the supply chain suffers from persistent vulnerabilities due to its decentralized and fragmented structure [1]. Recurrent challenges include:

- Adulteration and dilution of milk during transit.
- Unauthorized access to containers or lid swapping.
- Manual and undocumented handling at multiple points. These risks are further magnified in rural areas where:
  - Less than 40% of routes have reliable connectivity.
  - Over 70% of dairy operators lack digital traceability tools.

- Cloud-based and sensor-heavy systems are difficult to scale due to cost and infrastructure gaps.

Existing technologies—such as QR/barcodes and RFID systems—offer partial solutions but suffer from drawbacks:

- Lack of tamper evidence.
- Susceptibility to duplication or spoofing.
- High maintenance or hardware costs.
- Centralized data models prone to insider manipulation [2].

Recent studies in Indian agricultural supply chains have emphasized the need for highly scalable and low-cost blockchain infrastructures to support large transaction volumes and decentralized stakeholders [3]. Similar observations on the role of blockchain in improving transparency and traceability across agri-

food supply chains have been reported in prior studies [4].

Overcome these barriers, blockchain-enabled NFC smart lids offer a low-cost, tamper-evident, and offline-compatible alternative. These lids record sealing and handling events locally and use blockchain to ensure data integrity without requiring full-time connectivity. However, current systems operate reactively—only logging events without interpreting them. This paper extends the existing architecture by integrating artificial intelligence (AI) components to provide initiative-taking capabilities such as:

- Tamper prediction and anomaly detection.
- Fraud behaviour modelling.
- Demand forecasting and route optimization.
- Predictive maintenance of traceability hardware.

These enhancements aim to transform traceability into a more intelligent, resilient, and efficient framework tailored to India's rural dairy ecosystem.

### Background and Related Work:

#### A. Blockchain Fundamentals

Blockchain is a decentralized, append-only ledger where data blocks are cryptographically linked using hash functions, ensuring tamper detection [1]. Consensus mechanisms such as Proof of Work, Proof of Authority, and lightweight timestamp-based approaches enable decentralized trust while addressing scalability and transaction efficiency requirements [3].

#### B. Blockchain in Agricultural Supply Chains

In agri-food logistics, blockchain improves traceability and data integrity. Walmart–IBM's Food Trust pilot showed blockchain could cut contamination trace times from days to seconds [5]. Yet, most deployments rely on constant connectivity, limiting usability in rural areas. Recent blockchain-based agricultural frameworks further highlight the importance of scalable, low-

latency consensus mechanisms for large-scale agriculture supply chains in the Indian context [3].

#### C. IoT and Smart Packaging Technologies

IoT–blockchain systems automate logistics via sensors, but are often costly, power-intensive, and dependent on stable networks—making them impractical for rural deployment. Smart packaging using NFC provides a passive, low-cost, and offline-capable alternative. Tamper-evident lids and short-range NFC scans support physical integrity verification even without connectivity [2]. Earlier agri-food traceability systems combining short-range identification technologies with blockchain have demonstrated practical improvements in supply chain visibility [6].

#### D. Research Gaps

- Despite technical advances, key gaps persist:
- Most systems lack integrated tamper detection.
- Offline-capable, low-cost traceability is rare.
- Centralized architectures remain vulnerable to insider edits.
- Consumer verification is weak—QR/barcodes are easily spoofed.

#### E. TinyML and Edge AI

TinyML refers to machine-learned models that have been optimized to run inference on ultra-low-power microcontrollers (for example, ARM Cortex-M class MCUs) with memory footprints measured in kilobytes. Typical TinyML workloads for the smart lid include lightweight anomaly classifiers (1D-CNNs or small fully connected networks), simple thresholding autoencoders for unexpected vibration patterns, and battery health predictors. Models are trained offline in the cloud on aggregated labelled datasets, then converted (e.g., TFLite Micro) and deployed to the lid for on-device inference.

Edge AI refers to pushing inference and short-loop decisions to devices or nearby mobile gateways (the stakeholder app) rather than the cloud. This reduces

latency, preserves privacy, and enables offline operation during connectivity gaps. Federated updates or periodic model aggregation allow the global model to improve without centralizing raw sensor data, striking a balance between local autonomy and system-level learning.[7].

#### F. Novelty and Originality

Unlike typical RFID + blockchain deployments that often require active readers and a denser infrastructure footprint (and can still be vulnerable to tag swapping or cloning), our solution uses a passive NFC smart lid coupled with a hardware tamper switch and local event storage to provide provable, container-level tamper evidence. Compared with QR-based methods—which are inexpensive but easily duplicated and lack any physical tamper signal—our approach ties a physical tamper state and event log to a blockchain anchor, preventing simple spoofing. Unlike sensor-heavy, cloud-centric IoT architectures that demand continuous connectivity and higher cost (battery, cellular), the proposed system leverages TinyML and delayed synchronization to operate offline and at low cost while still providing auditable, blockchain-anchored proofs of custody.

#### Problem Statement and Objectives:

India's dairy supply chain continues to face persistent traceability challenges due to its highly decentralized structure and limited digital infrastructure. Despite existing efforts, several systemic weaknesses hinder secure, transparent, and scalable operations.

#### A. Persistent Challenges

- **Adulteration and Tampering:** Containers are frequently accessed or altered during transit without leaving digital evidence.
- **Manual Recordkeeping:** Informal, paper-based custody logs lead to unverified handling events and accountability gaps.

- **Connectivity Barriers:** Rural areas lack reliable networks, rendering cloud-based IoT systems infeasible.
- **Technological Mismatch:** RFID/GPS-based systems are costly and difficult to scale in low-resource contexts.

#### B. Limitations of Current Solutions

Existing technologies—including QR/barcode systems and centralized platforms—fail to provide tamper evident, verifiable, and offline-operable traceability. Centralized databases are also vulnerable to insider manipulation, undermining data trust.

#### C. Enhanced Objectives with AI Integration

Addressing these gaps, this work extends a blockchain-enabled NFC smart lid system by integrating artificial intelligence. The enhanced architecture aims to:

- **Predict and detect tampering** based on event patterns, enabling early intervention.
- **Improve operational efficiency** through AI-driven route optimization and resource allocation.
- **Detect anomalies automatically** across handling and custody events to flag inconsistencies or risks.
- **Forecast demand and monitor reliability**, enabling better scheduling and inventory control.
- **Support predictive maintenance** for hardware components, reducing downtime and improving lifecycle efficiency.

These AI enhancements aim to transform traceability from passive logging to intelligent, initiative-taking assurance, while remaining lightweight and compatible with rural constraints.

## Proposed System Architecture:

### A. System Overview

The proposed system integrates low-cost, reusable, NFC-enabled smart lids with blockchain-backed traceability to address the core limitations of India's rural dairy supply chain. It ensures tamper-evident, offline-compatible, and verifiable tracking of milk containers across production, transport, and distribution. The architecture is composed of three main layers:

- **Smart Lid (Edge Hardware):** Each container is sealed with a programmable NFC tag and tamper switch. The lid logs sealing, tampering, and scan events to internal memory.
- **Mobile Gateway (App Layer):** Stakeholders (e.g., collectors, transporters, processors) use a mobile app to scan the lid, read/write events, and upload logs when network is available.
- **Blockchain Backend:** Uploaded events are verified, hashed, and stored on a permissioned or hybrid blockchain to ensure integrity, ordering, and traceability.

This design enables decentralized, trust less recording of custody and event histories—even in regions with poor connectivity.

### B. AI Layer Integration

Transform the system from passive logging to initiative-taking intelligence, AI is integrated at multiple levels:

- **Edge AI (Smart Lid):** TinyML models perform on-device tamper prediction, anomaly scoring, and lid health monitoring.
- **Mobile App AI:** Local models flag anomalies during scans and support route guidance, even

offline. Federated learning can refine shared models without centralizing raw data [8].

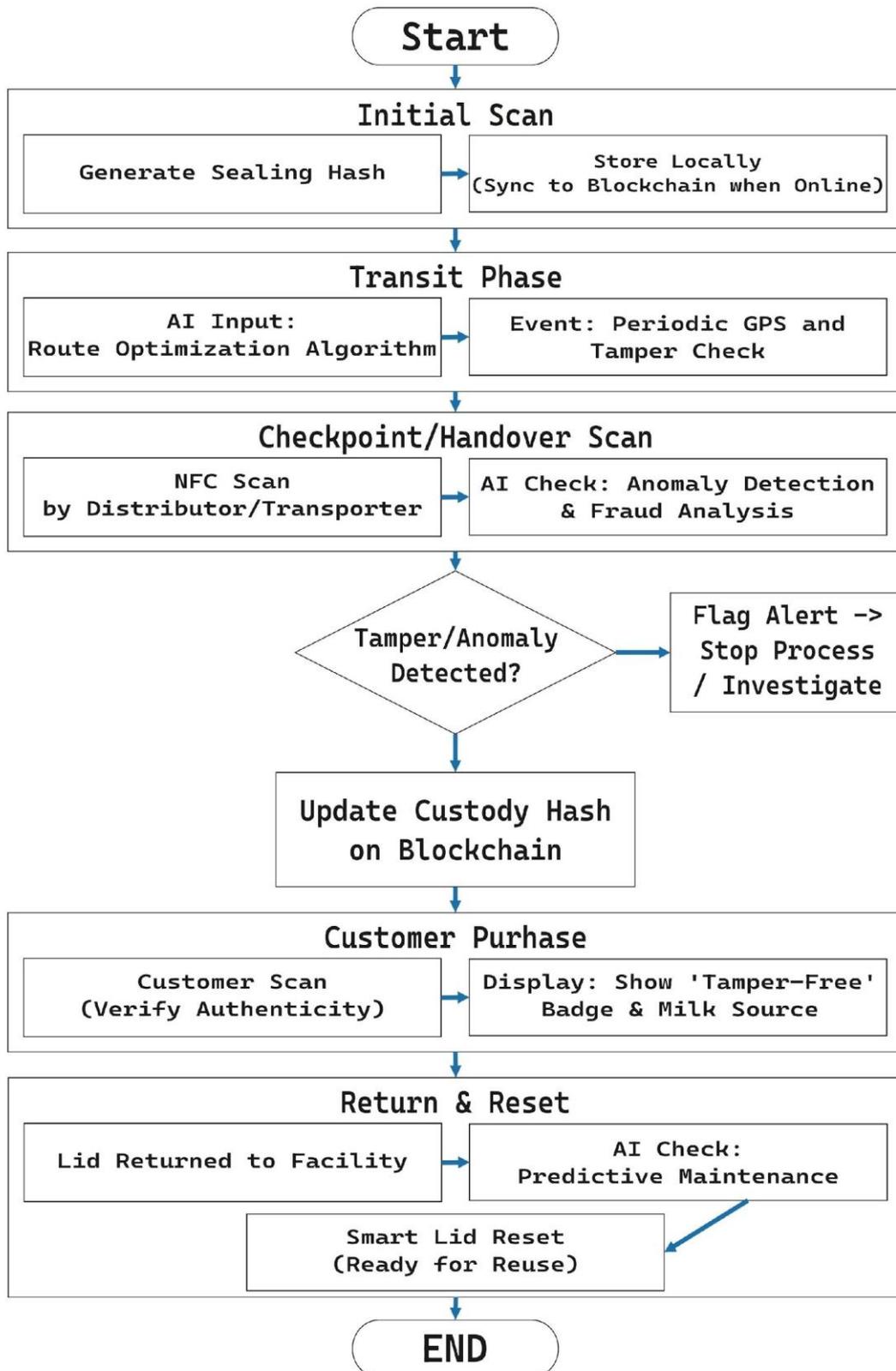
- **Backend AI Services:** More complex models run on the cloud, handling fraud detection, inventory forecasting, lifecycle analysis, and logistics optimization.

All AI-generated alerts or decisions are optionally hashed and stored on the blockchain to ensure transparency and auditability.

### C. Traceability Workflow

The system ensures a secure, verifiable chain-of-custody through the following steps:

- **Packing and Sealing:** The worker initializes the lid, and the sealing hash (including Batch ID and Plant ID) is recorded immutably on the blockchain [1].
- **Tamper Monitoring:** Any unauthorized opening is instantly captured by the tamper switch and stored locally on the lid [2].
- **Custody Transfer:** Drivers or retailers scan the lid via NFC. The mobile app retrieves stored logs and submits the transfer hash to the blockchain [5].
- **Transit Monitoring:** The driver's application periodically records checkpoint data (GPS + event summaries) whenever network connectivity is available.
- **Consumer Verification:** End-users tap the lid using their smartphones to verify real-time tamper status and a blockchain-backed authenticity badge [9].
- **Return and Reuse:** After delivery, the collection agent logs the can return, resetting the smart lid for subsequent reuse cycles.



*Fig. 1. Smart Lid Blockchain-Enabled Supply Chain Workflow*

#### D. Hypothetical Use Case: NFC-Enabled Dairy Supply Chain

Consider a short, illustrative flow from village to retailer in a dairy supply chain using NFC-enabled smart lids.

- **Village/Collection:** Farmers seal milk cans with NFC smart lids. The sealing event and Batch ID are recorded in the lid's local log.
- **Transport to Cooperative:** The driver scans each lid. A mobile gateway reads the offline logs and applies a TinyML tamper check, flagging any suspicious lids.
- **Cooperative:** Scanned and validated events are batched and committed to a permissioned blockchain whenever connectivity is available.
- **Inter-Facility Transit:** Edge AI on the driver's phone monitors route deviations and delay anomalies. Logs are periodically anchored to the blockchain.
- **Processor:** Incoming cans are re-scanned; the blockchain anchor verifies the custody chain and tamper status prior to processing.
- **Retail/Consumer:** Consumers tap the lid to verify batch provenance and tamper history via the authenticity badge.

This flow illustrates a conceptual validation of a secure, traceable dairy supply chain leveraging NFC, TinyML, and blockchain technology.

#### AI Modules and Functional Enhancements:

Move beyond passive event logging, the system integrates AI-driven functionality that enhances traceability, security, and operational efficiency across the supply chain. These modules operate at different layers of the architecture and enable real-time insights even in low-connectivity environments.

#### A. Tamper Prediction and Detection

AI identifies unusual handling patterns, irregular scan intervals, or route deviations to predict or

detect potential tampering events early, strengthening container security.

#### B. Anomaly Detection in Event Logs

The system automatically flags abnormal custody events—such as missing scans or inconsistent timestamps—helping stakeholders detect operational issues or manipulation.

#### C. Fraud Detection

Behavioural patterns such as repeated lid resets, suspicious scanning behaviour, or unusual route repetitions are analysed to identify potential insider fraud or collusion.

#### D. Route Optimization

AI assists transporters by recommending efficient delivery routes that reduce delays and maintain product quality, particularly in unpredictable rural conditions.

#### E. Demand Forecasting

Historical and regional patterns are analysed to help cooperatives anticipate demand variations, plan inventory, and reduce wastage.

#### F. Predictive Maintenance

AI monitors basic lid health indicators to detect signs of battery depletion or component wear, allowing initiative-taking maintenance and minimizing hardware downtime.

Together, these AI modules enhance the reliability, transparency, and intelligence of the traceability system while maintaining compatibility with low-resource rural environments.

#### Blockchain Architecture:

The blockchain layer provides a secure and verifiable backbone for recording all traceability-related events generated by the smart lid and AI modules. Instead of storing raw data, each interaction—such as sealing, tampering, or custody transfer—is represented as a cryptographic hash and appended to the blockchain, ensuring tamper-evidence and auditability.

A lightweight permissioned blockchain is used to maintain low computational overhead and support deployment in resource-constrained rural environments. Authorized stakeholders function as validating nodes, enabling decentralized trust without relying on continuous internet connectivity.

AI-generated insights, such as anomaly alerts or tamper-risk scores, can also be anchored to the blockchain, creating transparent and verifiable decision trails without exposing sensitive operational data. Preserve privacy, only hashed references are stored on-chain, while detailed metadata remains securely off-chain.

The architecture supports offline operation through local event storage and delayed synchronization. Once connectivity is available, batched events are committed to the blockchain in chronological order, maintaining both data integrity and system reliability across the supply chain.

#### Implementation Overview:

The smart lid serves as a simple, low-cost physical interface designed to securely capture sealing, opening, and handling events. It incorporates basic NFC capabilities and a tamper-detection mechanism, allowing event logs to be stored locally and retrieved during NFC scans even without connectivity. The lid is lightweight, reusable, and optimized for offline operation, enabling seamless handovers across stakeholders while providing reliable data to the AI and blockchain layers without relying on complex hardware components. VIII. Limitations and Future Work

#### A. System Limitations

Despite encouraging results, several challenges remain:

- **Model Robustness:** Limited labelled data can lead to false positives in tamper and anomaly detection.

- **Edge Constraints:** Memory and compute limitations restrict AI model complexity on-device.
- **Human Variability:** Inconsistent scanning practices across operators may affect event quality.

#### B. Future Enhancements

Address these gaps and enhance scalability:

- **Multi-Modal AI:** Combine NFC scans with sensor data (e.g., accelerometer, temperature) for richer context.
- **Fixed Scanning Stations:** Deploy at cooperative centres for consistent event capture.
- **Voice-Based Interfaces:** Use lightweight NLP for alerts and user feedback in regional languages.
- **Federated Learning:** Train models locally and share gradients instead of raw data for privacy-preserving adaptation.

#### Conclusion:

This work presents an AI-augmented traceability framework combining blockchain, NFC-enabled smart packaging, and edge intelligence tailored for India's decentralized dairy supply chain.

By fusing tamper-evident hardware, verifiable event anchoring, and predictive AI modules, the system achieves:

- Enhanced security through early tamper detection and fraud prevention.
- Improved transparency via blockchain-backed, auditable data trails.
- Operational efficiency gains from intelligent routing and forecasting.

Designed for low-resource, intermittently connected environments, this architecture offers a scalable, cost-effective path toward intelligent, secure, and inclusive supply chains in rural economies.

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