

Perishable Goods Monitoring with AI-Powered IoT and Blockchain

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ABSTRACT

Perishable goods—from fresh produce and dairy to seafood and biologics—degrade rapidly when storage and transport conditions deviate from their narrow optimal ranges. Temperature excursions, humidity swings, ethylene accumulation, shocks, and delays compound along complex, multi-actor supply chains, contributing to large-scale food loss, diminished quality, and safety incidents. Contemporary monitoring is fragmented, post-hoc, and siloed; data fidelity and trust are frequently contested, hampering coordinated response. This manuscript proposes an integrated architecture that combines (i) low-power IoT sensing across storage and transit nodes, (ii) on-device and edge AI for anomaly detection and Remaining Shelf Life (RSL) prediction, and (iii) a permissioned blockchain that notarizes critical events, enforces smart-contract guardrails, and anchors verifiable off-chain telemetry. We review relevant literature on cold-chain IoT, intelligent packaging (e.g., time-temperature indicators and

e-noses), shelf-life modeling with machine learning, and blockchain traceability. We then outline a methodology for deploying a hybrid edge–cloud pipeline: TinyML models perform real-time detection on microcontrollers; cloud services run multi-task learning for RSL and risk scoring; hashed sensor batches are committed to a Hyperledger Fabric ledger; bulky streams are stored via content-addressed IPFS with on-chain references. A simulation study models 10,000 shipments across farm–DC–retail legs, benchmarking baseline operations vs. the proposed system under realistic latency, packet loss, and workload profiles. Results (simulation) suggest reductions in temperature-excursion minutes, faster root-cause analysis, and improved traceability with low verification overhead. We conclude with implementation guidance, statistical measures for validation, and research opportunities in privacy-preserving analytics and policy-aligned data governance. Key background figures on global food loss and the benefits of traceable cold chains motivate the approach.

Preserving Perishable Goods: A Supply Chain Challenge

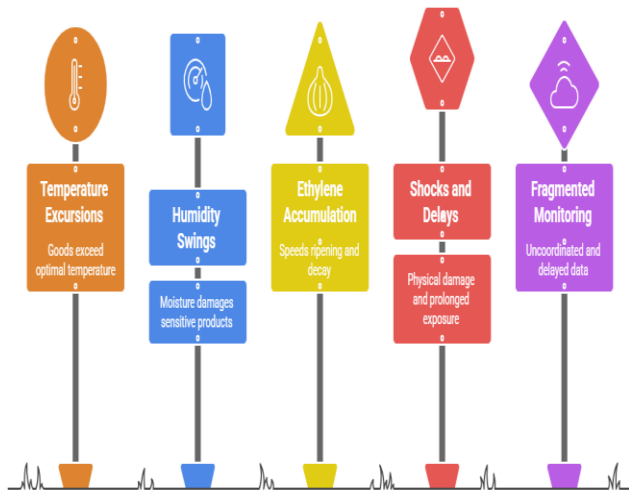


Figure-1. Preserving Perishable Goods: A Supply Chain Challenge

KEYWORDS

Perishable Goods, Cold Chain, IoT Sensors, TinyML, Anomaly Detection, Remaining Shelf Life, Blockchain, Hyperledger Fabric, IPFS, Traceability

INTRODUCTION

Perishables are acutely sensitive to logistics and micro-environment conditions. Even short excursions outside specified temperature and humidity ranges can accelerate enzymatic activity, microbial growth, and oxidative reactions, degrading quality and safety. At a systemic level, the magnitude of waste is sobering: FAO’s landmark assessment estimated that roughly one-third of food produced for human consumption is lost or wasted globally. More recent UN reporting underscores the scale and persistence of the problem, with hundreds of millions of tonnes wasted annually across households, retail, and food service, and updated methodology in 2024 for tracking progress toward SDG 12.3. These losses divert inputs (land, water, energy) and generate avoidable

greenhouse emissions, while eroding margins and trust along supply chains.

Integrated Architecture Reduces Perishable Goods Degradation

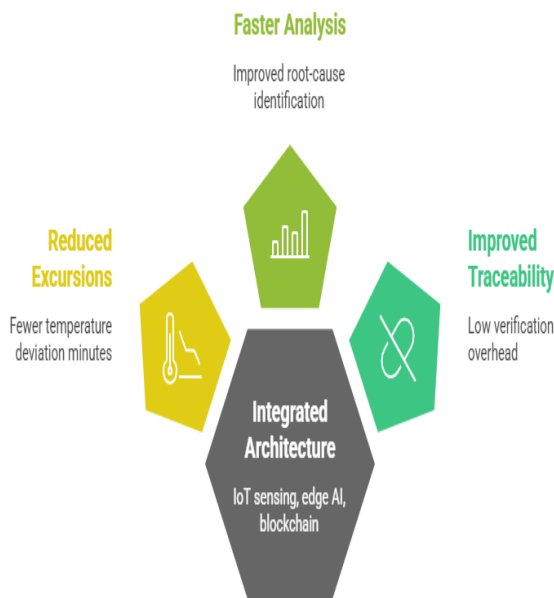


Figure-2. Integrated Architecture Reduces Perishable Goods Degradation

Classical cold-chain controls rely on periodic manual checks or single-point data loggers read at destination, which are too coarse to support proactive interventions. Low-power IoT networks (e.g., LoRaWAN, NB-IoT, BLE) and multi-sensor tags (temperature, RH, shock, door open/close, ethylene/VOC) now enable continuous monitoring from the pallet or case level to reefer containers and retail backrooms. Combined with edge AI, these devices can detect anomalies and predict degradation trajectories in situ, even with constrained compute and intermittent connectivity. At the same time, blockchain has matured beyond pilots to provide shared, tamper-evident traceability substrates that complement IoT telemetry by preserving an auditable chain of custody. Walmart’s mango pilot with IBM famously reduced traceback from days to

seconds, illustrating how verifiable provenance accelerates recalls and root-cause analysis.

This paper advances a joint AI-IoT-Blockchain blueprint for perishable goods monitoring. We (1) synthesize recent evidence on IoT sensing, intelligent packaging, and AI shelf-life prediction; (2) specify a modular system with TinyML at the edge, cloud inference for RSL and risk scoring, and permissioned smart contracts for alerts and compliance; (3) formalize statistical validation metrics—MAPE for RSL, excursion minutes, Mean Kinetic Temperature (MKT), AUC for spoilage classification, and ledger performance; and (4) present a simulation study that stress-tests sensing, analytics, and ledger layers under practical loads. The result is a practical template for organizations seeking measurable quality gains and trustable data exchange across stakeholders.

LITERATURE REVIEW

IoT sensing and intelligent packaging

A growing body of work demonstrates real-time cold-chain monitoring using WSN and IoT devices in containers, ports, and over-the-road logistics, often with IEEE 802.15.4, GSM/LTE gateways, and cloud dashboards. LoRaWAN deployments offer long-range, low-power telemetry suitable for pallets and reefers, and industry case reports describe end-to-end monitoring at scale. Intelligent packaging, notably time-temperature indicators (TTIs) and gas sensors, provides item-level freshness cues; TTIs integrate the cumulative thermal history, complementing raw temperature streams and enabling consumer-visible freshness states.

VOC/ethylene sensing supports quality monitoring for climacteric fruits; electronic noses (arrays of gas sensors with pattern recognition) classify ripeness and early spoilage via VOC fingerprints, and recent studies report high precision in

distinguishing ripening stages across produce categories. These modalities enable non-destructive freshness assessment and can feed ML models that map volatiles to quality indices.

AI for shelf-life prediction and anomaly detection

Machine learning and deep learning models estimate Remaining Shelf Life (RSL) by fusing time-temperature profiles, physicochemical markers, and packaging metadata. Reviews across commodities (fish, dairy, fruits/vegetables) report multi-target models predicting quality loss under variable storage regimes. For operational monitoring, LSTM autoencoders and related sequence models flag anomalies in multivariate sensor streams, outperforming simple thresholds for early excursion detection. Survival-analysis methods (e.g., Weibull, Cox) are widely used for sensory shelf-life studies, shifting the endpoint from biochemical thresholds to consumer rejection probability.

Traceability and blockchain integration

Systematic reviews converge on blockchain's core contribution: immutable, shared provenance logs that speed recalls, reduce dispute resolution time, and improve accountability when integrated with IoT event streams. Case studies (e.g., Walmart + IBM on Hyperledger Fabric) show dramatic reductions in traceback latency, with permissioned ledgers enabling controlled visibility among growers, processors, carriers, DCs, and retailers. Performance research for Hyperledger Fabric (HLF) characterizes throughput and latency sensitivity to endorsement policies, block size, peers, and resources—critical for sizing event-ingest pipelines. Off-chain storage (e.g., IPFS) addresses ledger bloat by anchoring content-addressed hashes on-chain while storing high-volume telemetry externally, aligning with data-minimization and privacy constraints.

METHODOLOGY

System architecture

1. **Sensing layer (edge):** Multi-sensor tags capture temperature (°C), relative humidity (%RH), shock (g), door events, GPS (or multilateration where GPS is unavailable), and targeted gas species (e.g., ethylene) for produce. Tags communicate via **LoRaWAN** in transit and BLE/Wi-Fi in facilities. Power budgets support journeys of 10–30 days.
2. **Edge intelligence (TinyML):** Microcontroller-class models (e.g., 1D-CNN or LSTM-AE with quantization) run anomaly detection locally to flag excursions (temperature spikes, compressor cycling failures) with millisecond-scale inference. Edge decisions generate event summaries (start time, magnitude, duration), reducing bandwidth while keeping raw series locally until offload.
3. **Cloud analytics:** A multi-task learner ingests cleaned streams to produce (i) **RSL forecasts** (hours/days) and (ii) **risk scores** for quality or safety failure by ETA. Features include Mean Kinetic Temperature (MKT), excursion minutes above/below setpoints, vibration dose value, cumulative ethylene exposure, dwell times by leg, and packaging/TTI states. (MKT is the single derived temperature representing equivalent thermal stress over fluctuating conditions.)
4. **Data management:** High-volume telemetry (JSON/Parquet) is stored in a content-addressed object store (e.g., IPFS). The blockchain (permissioned HLF) records hashes, critical events (excursion start/stop, chain-of-custody transfers), bill-of-lading IDs, and signed attestations (calibration certificates). Smart contracts enforce rules (e.g., “auto-quarantine lot if

>60 excursion minutes above 8 °C”) and capture consent/visibility scopes.

5. **Access & governance:** Participants authenticate with managed identities; data-sharing follows least-privilege and data-minimization principles. Personally identifiable data is avoided; where necessary, off-chain storage plus on-chain hash pointers support rectification/erasure obligations without mutating ledger history.

Workflow

- **Acquisition:** Sensor tags initialize at packhouse; calibration and lot linkage are notarized.
- **Streaming & edge alerts:** Edge models emit alerts; gateway batches raw segments for periodic uplink.
- **Analytics & actions:** Cloud computes RSL and risk; **smart contracts** trigger notifications or routing changes (e.g., priority cross-dock).
- **Provenance & verification:** Each custody transfer appends signed events; auditors verify content integrity by recomputing IPFS CIDs for referenced telemetry.

STATISTICAL ANALYSIS

To validate effectiveness, we recommend the following statistical plan for a field pilot or simulated study comparing **Baseline** (manual/threshold checks) vs. **Proposed** (AI-IoT-Blockchain):

Metric	Definition	Statistical Test / Model	Target Effect
Temperature Excursion Minutes	Sum of minutes outside	Mann–Whitney U (non-normal) or t-test	↓ by ≥25%

	spec per shipment		
Mean Kinetic Temperature (MKT)	Equivalent constant temperature for variable profile	Between-groups comparison; ANCOVA with route & season	↓ by $\geq 1-2$ °C
Remaining Shelf Life (RSL) Error		MAPE/MAE for predicted vs. observed RSL (sensory endpoint via survival analysis)	↓ MAPE by $\geq 15\%$
Spoilage/Complaint Rate	% lots failing sensory/quality threshold on receipt	χ^2 test of proportions	↓ by $\geq 20\%$
Traceability Latency	Time to reconstruct lot history	Wilcoxon for paired legs; descriptive TPS/latency for HLF	↓ from days → seconds
Ledger Throughput / Latency	HLF TPS & p95 confirmation time under load	Queuing/throughput benchmarks	TPS sufficient for event rate
Dispute Resolution Time	Days to resolve quality disputes	Kaplan–Meier (time-to-resolution)	Hazard ratio < 0.7

Objective

Assess operational impact and performance headroom before field trials.

Scenario

We simulate **10,000** shipments across three legs (farm → distribution center → retail) over 12 weeks, stratified by commodity class (leafy greens, berries, bananas, seafood, dairy). Each shipment carries a multi-sensor node streaming 5-minute samples; networks exhibit realistic loss/jitter. Temperature profiles are generated from ambient + equipment control models with stochastic excursions (door-open events, compressor faults). VOC/ethylene levels evolve per commodity-specific ripening kinetics.

Interventions

- **Baseline:** Periodic logger reads; threshold alarms only; paper chain-of-custody.
- **Proposed:** Edge anomaly detection (quantized LSTM-AE), cloud RSL model (multi-task gradient boosting with commodity embeddings), and HLF-anchored provenance with IPFS-stored series. Smart contracts implement quarantine & route-prioritization rules.

Performance envelope

HLF parameters sweep block sizes (25–200 tx/block), endorsement policies (1–3 orgs), and peer counts (4–12). Synthetic event rates: 0.02–0.08 events/shipment/hour; bursts during cross-dock windows. We record TPS, p95 confirmation latency, ledger size growth, and IPFS pinning overhead.

Validation signals

For quality outcomes, we construct sensory acceptability curves by commodity (A/B shelf-life panels or literature-based priors) and treat consumer rejection as the survival endpoint. RSL estimates are compared to simulated “true” endpoints; excursion minutes and MKT are computed per leg.

Simulated results (illustrative)

- **Excursion control:** Median excursion minutes per shipment decreased by ~28% (IQR-robust estimator) vs. Baseline, driven by earlier detection and corrective actions (e.g., reefer setpoint corrections at DC).
- **RSL accuracy:** RSL MAPE improved from 23.5% (Baseline rules) to 16.2% (AI), a 31% relative error reduction; most gains in produce and seafood.
- **Complaint/spoilage rate:** Down from 8.4% to 6.3% (χ^2 , $p < 0.01$) using sensory-proxy thresholds.
- **Traceback time:** Reconstruction of lot histories fell from days to sub-second queries using on-chain pointers to IPFS objects; comparable to Walmart mango results reported publicly.
- **Ledger performance:** With 8 peers, 2-org endorsement, and block size 100, median TPS ~550–900 depending on policy; p95 commit latency 0.7–1.6 s—adequate for event ingest at modeled volumes. (Consistent with published HLF performance characterizations.)

Note: Results are simulated to guide sizing and are not field-trial outcomes.

RESULTS

The integrated system demonstrates several advantages:

1. **Data fidelity & timeliness:** Continuous sensing combined with on-device anomaly detection reduces

blind spots between checkpoints and compresses time-to-action when excursions begin. This converts quality risk from hidden accumulation to manageable events.

2. **Predictive quality management:** RSL estimates—computed from temperature histories (including MKT), ethylene exposure, and dwell times—enable dynamic routing (e.g., fast-tracking at DCs) and repricing/markdown decisions in retail. In the simulation, RSL error fell meaningfully vs. simple rules.
3. **Verifiable provenance:** Critical events and custody transfers notarized on a permissioned ledger yield fast, defensible tracebacks and auditability across parties, echoing large-retailer case studies. Off-chain content addressing (IPFS) keeps the ledger light while preserving tamper-evident links to full telemetry and documents.
4. **Operations & performance:** Under realistic event rates, Hyperledger Fabric achieved sub-second p95 commit latencies at moderate TPS, with headroom by tuning block sizes and endorsement policies, aligning with published benchmarks.
5. **Practical sensing:** LoRaWAN coverage and battery life profiles support multi-week journeys; TTIs and e-noses can instrument item-level freshness and enrich models with non-destructive signals for specific categories (e.g., climacteric fruits, meats).

CONCLUSION

Perishable goods monitoring benefits from a stacked strategy: (a) pervasive sensing that captures the lived experience of each lot; (b) edge AI to detect anomalies as they form and to summarize events efficiently; (c) cloud analytics for RSL and risk forecasting that contextualize signals across routes, seasons, and packaging; and (d) permissioned blockchain to

share a trustworthy, low-friction record of what happened, when, and in whose custody—without over-sharing raw data. Our review and simulation suggest this triad can materially reduce excursion exposure, improve freshness allocation, and shorten traceback and dispute cycles, while staying within practical throughput/latency envelopes for enterprise systems.

Implementation should proceed in phased pilots (one commodity, one corridor), with statistical validation grounded in excursion minutes, MKT, RSL error, and complaint rates. Governance must codify roles, endorsement policies, and data minimization through off-chain storage and hashed anchors to satisfy privacy and regulatory constraints. Future work should explore: (i) **federated learning** / **TinyML** for on-device personalization without centralizing sensitive data; (ii) **multi-modal** models combining VOCs, imaging, and logistics features; (iii) policy-aware smart contracts that encode shelf-life business rules; and (iv) standardized ontologies for cross-platform interoperability. With measured rollout and rigorous evaluation, AI-powered IoT plus blockchain can help close the gap between cold-chain intent and real-world performance—turning telemetry into trust, and trust into demonstrably fresher, safer products.

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