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A Hybrid Metaheuristic–Blockchain Smart Contract Framework for Secure Farmer-to-Consumer Transportation in Agri-Supply Chains

Shailaja Pede[1], Dr.Yogini Borole[2]

[1]Research Scholar, School of Science & Technology, Glocal University, Saharanpur, Uttar Pradesh, India
[2]Professor, School of Science & Technology, Glocal University, Saharanpur, Uttar Pradesh, India

Abstract
The transparency of the agricultural supply chain is limited, post-harvest losses are high, and settlement is delayed during transportation from the farmers to the consumers, with risks of data-integrity issues. This paper introduces a hybrid model of metaheuristic route optimization, IoT monitoring, and blockchain smart contracts. A Hybrid Particle Swarm Optimization–Genetic Algorithm (HPSO-GA) is used to solve the problems of vehicle assignment and delivery route optimization under the conditions of capacity, time window, cold chain constraints and perishability.The verifiable batch events are recorded by smart contracts, the escrowed payment is managed by smart contracts, the quality conditions are enforced by smart contracts, and the dispute is solved by smart contracts. High volume sensor data remains off-chain with only decision relevant hashes on-chain, maintaining integrity while being scalable. The architecture, process, optimization model, contract design, security analysis and a reproducible evaluation protocol with an illustrative results template are presented in this paper, presented by means of the system diagrams and comparative charts. The illustrative results show the hybrid approach can lead to lower routing cost, delivery time, and exposure of spoilage compared to single-strategy baselines with relatively small computation time.

Keywords: Blockchain; Smart Contracts; agri-supply chain; Vehicle Routing; Hybrid Metaheuristic Optimization; Particle Swarm Optimization; Genetic Algorithm; IoT; Traceability; Cold Chain; Farmer-To-Consumer Distribution.

1. Introduction

The farmer-consumer distribution of fresh produce is complicated by its perishability, the lack of a centralized information system that farmers and consumers can trust, its fast changing demand, and the geographical dispersion of farms. Its fragmented records make it hard to trace origin, handling conditions, route execution, and final delivery, leading to food loss, delayed farmer payment and decreased consumer confidence.

Smart contracts can be used to set up rules for accepting delivery evidence and release payment, while blockchain-based traceability can generate an append-only audit trail. However, blockchain is not the answer to the choice of which vehicle to deliver to which customer or which route is best suited to ensure that perishable products remain cold, with a limited capacity and time constraint—an LPVRP that is interesting because the exact optimization is costly at scale, making hybrid versions of metaheuristics more appealing.

This paper introduces a hybrid framework, combining elements of both metaheuristics and blockchain technology, which optimizes farmer-to-consumer transportation off-chain using a Hybrid Particle Swarm Optimization–Genetic Algorithm (HPSO-GA), submits signed route commitments and event hashes on-chain, and utilizes smart contracts to manage custody, quality-based settling, and dispute resolution closing the loop in the planning, execution, and settlement of farmer-to-consumer transportation.

1.1 Objectives and Contributions

- An HPSO-GA method for multi-objective routing and vehicle assignment, and a layered architecture connecting IoT sensing, optimization, off-chain storage, and blockchain smart contracts.
- A modular smart-contract design (five modules) for batch registration, custody transfer, route commitment, quality evidence, escrow, and disputes.
- A security and privacy analysis, plus a reproducible evaluation protocol and illustrative results template covering transportation, traceability, security, and blockchain-cost metrics.

2. Related Work and Research Gap

The most frequent examples for blockchain applications in agri-food systems are tracking of food origins, traceability, recall of food products and transparency for actors on the food chain, including through permissioned designs balancing transparency with governance and the development of DApp prototypes that enable real-time, batch-level tracking. The approaches that rely on the Internet of Things (IoT) expand the data observed beyond the raw streams to include additional information such as temperature, humidity, location, and handling data, and usually leave the raw streams off-chain with only content hashing on chain and then the events of handling, temperature or humidity changes and settling are subject to contracts that ensure the custody transfer.

Table 1. Representative directions in related work and their relationship to the proposed framework.

Research direction	Typical focus	Relation to this framework
Blockchain traceability for agri-food (incl. DApp prototypes)	Provenance, recall, transparency, on-chain event logging	Basis for BatchLifecycle, QualityOracle, and the dashboard layer
Permissioned blockchain for agricultural supply chains	Governance-aware ledger design for multi-stakeholder trust	Informs the permissioned vs. Ethereum-compatible choice (Section 5)
Digitalization / blockchain integration in agri-food supply chains	Broader digital-transformation framing of adoption	Contextualizes deployment limitations (Section 9)

Research direction	Typical focus	Relation to this framework
Stochastic optimization of perishable supply chains; hybrid Green AI distribution	Uncertainty- and sustainability-aware planning	Motivates the spoilage (S) and emissions (E) terms in the fitness function
Hybrid PSO with genetic operators for VRP	Algorithmic hybridization for general vehicle routing	Direct basis for the HPSO-GA method in Section 4.1
Modular Web3 architecture (blockchain + IoT + ML)	Layered integration of sensing, ledger, and analytics	Closest precedent for the four-layer architecture in Section 3.1

Separately, genetic algorithms, particle swarm optimization, ant colony optimization, and simulated annealing are applied extensively to vehicle-routing problems. Hybrid methods combining population-based global search (e.g., PSO) with genetic operators are attractive for pairing broad exploration with route-level exploitation, and stochastic or green-AI-oriented approaches have been proposed for perishable and sustainable distribution.

Table 1 summarizes representative directions. Most agri-food systems treat routing optimization and blockchain traceability as independent modules — optimization research rarely anchors output on a verifiable ledger, and traceability research rarely optimizes the movement generating its events. Modular Web3 architectures point toward tighter integration, but a mechanism in which optimized routes, delivery evidence, and settlement conditions are cryptographically linked and automatically enforced remains underexplored — the gap this framework addresses.

3. Proposed Framework

3.1 Architecture

The proposed framework uses four interoperating layers, illustrated in Figure 1: (1) a data and sensing layer, where farm, vehicle, and delivery-point devices capture batch identity, GPS, temperature, humidity, timestamps, and proof-of-delivery events; (2) an off-chain and edge layer that validates signatures, detects anomalies, stores raw files in a secure database or IPFS-compatible store, and computes content hashes; (3) an optimization layer executing HPSO-GA using current orders, capacity, product requirements, and time windows; and (4) a blockchain and application layer that stores identities, batch state, hashes, route commitments, and escrow status, serving farmer, carrier, consumer, and auditor dashboards. Only decision-relevant records and cryptographic hashes are committed on-chain, avoiding high-volume sensor storage while retaining tamper-evident links to the original evidence.

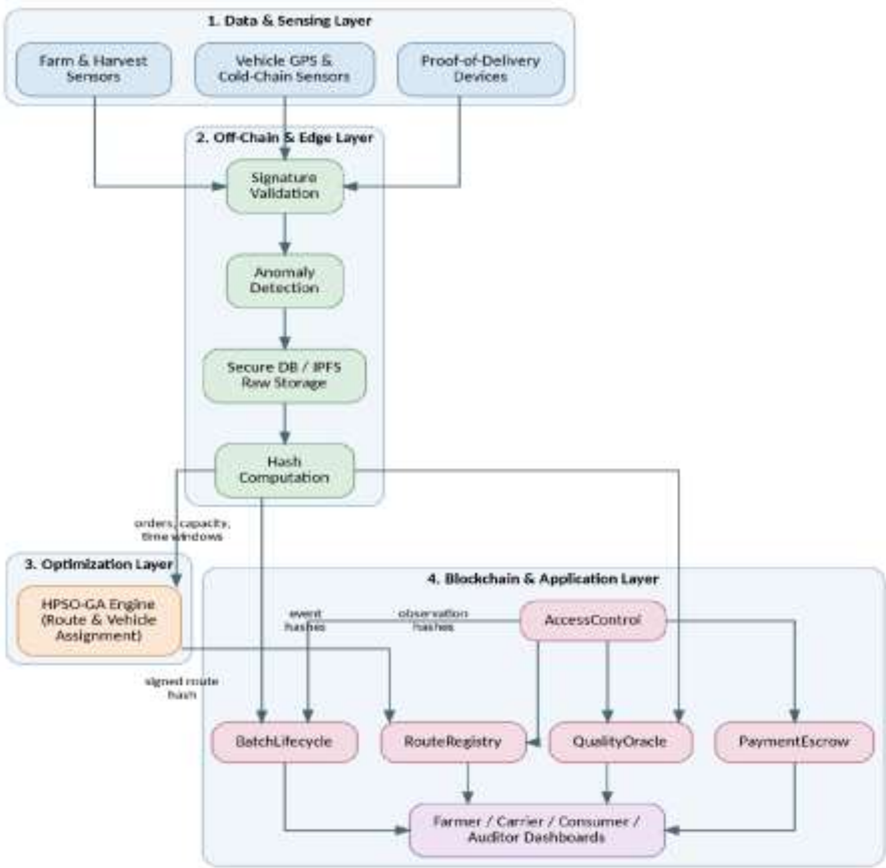

Figure 1. Four-layer system architecture showing data flow from sensing through optimization to the blockchain and application layer.

3.2 Operational Workflow

The workflow is summarized in Figure 2: A farmer registers a batch with a hash of supporting records; an order from a consumer funds a contract managed escrow, which is signed at delivery and triggers a payment release based on the quality score, or release or hold payment; any violation raises an alert; at delivery, signed proof of delivery triggers a payment release, or partial release or hold payment; any dispute preserves evidence references for an agreed arbitrator or governance mechanism.

Figure 2. Operational workflow from batch registration to escrow settlement, with an optional dispute-resolution branch.

4. Optimization Model

The transportation problem is modeled as a capacitated vehicle-routing problem with time windows and with perishability constraints (CVRPTW-P). Let N be the delivery nodes, K the number of available vehicles, d_{ij} the distance between nodes i and j, t_{ij} the time it takes to travel between nodes i and j, q_i the demand for customer i, Q_k the capacity of vehicle k, and $[e_i, l_i]$ the service time window of customer i. A feasible route is one that satisfies the following requirements: It visits each customer exactly once; It meets the capacity constraints; It satisfies the time windows; It does not violate any maximum exposure times for the products. The fitness function is a multi-objective type fitness function, which is the combination of the following five terms:

$$\mathbf{F = w_1C + w_2T + w_3E + w_4S + w_5P}$$

where C is transportation cost, T is delivery time, E is estimated emissions, S is spoilage/quality-loss penalty, P is a constraint-violation penalty, and w_1–w_5 are stakeholder-defined weights. Since these objectives can conflict, a Pareto-ranking implementation with a nondominated archive may be used instead of a single weighted scalar.

4.1 HPSO-GA Method

Particles encode route sequences and vehicle assignments. PSO guides the population toward high-quality personal- and global-best route structures, while GA periodically applies selection, crossover, and mutation to maintain diversity. Feasibility-repair operators correct violations after each update, and local-search moves (2-opt, relocation, exchange) refine elite routes, as summarized in Figure 3 and detailed in Appendix A. The optimizer runs off-chain — its budget can be tuned to the planning window without on-chain cost, with only the final route commitment anchored on-chain (Section 5).

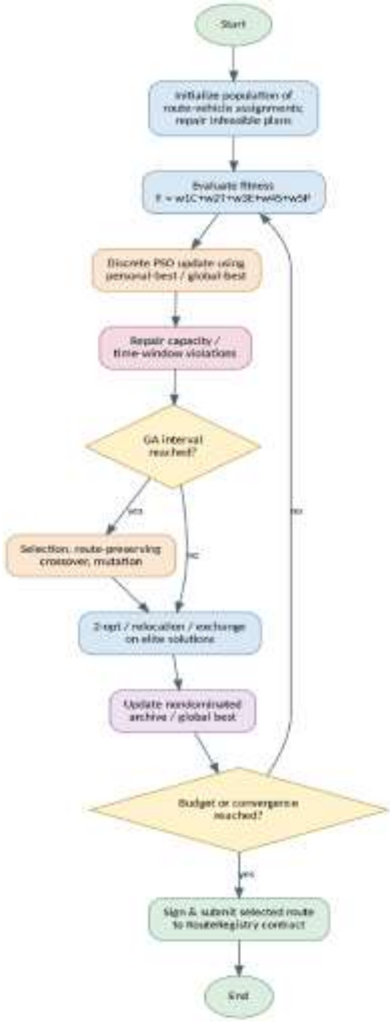

Figure 3. HPSO-GA algorithm flow: PSO-driven global search, periodic genetic operators, feasibility repair, local search, and archive update.

5. Smart-Contract Design

Contracts should be deployed on a permissioned blockchain or an Ethereum-compatible chain per governance, privacy, and cost needs. Table 2 separates responsibilities into five logical modules for auditability.

Table 2. Smart-contract modules, core responsibilities, and illustrative function signatures.

Module	Core responsibility	Illustrative functions
AccessControl	Role-based authorization for farmers, carriers, buyers, inspectors, and arbitrators.	grantRole(), revokeRole(), verifyRole()
BatchLifecycle	Immutable product-batch creation and custody-state transitions.	createBatch(), updateCustody(), recordEvent(), getHistory()
RouteRegistry	Anchoring of optimized route commitments and authorized dispatch.	submitRouteHash(), assignVehicle(), confirmDeparture()
QualityOracle	Validation of signed sensor summaries and rule-based quality scoring.	submitObservationHash(), evaluateQuality(), raiseAlert()
PaymentEscrow	Conditional settlement and dispute holds.	fundEscrow(), confirmDelivery(), releasePayment(), openDispute()

The optimizer stays off-chain since iterative metaheuristic search is expensive to run in a smart-contract environment; the chain instead records the optimizer version, signed input-data hash, output route hash, timestamp, and authorized submitter for later audit. AccessControl mediates every write to the other four modules, so a role compromise in one cannot silently alter another.

6. Security and Privacy

- Data integrity: SHA-256 (or equivalent) content hashes for route files, sensor bundles, and delivery evidence, with originals stored off-chain under access control.
- Authenticity and access control: mandatory device/stakeholder signatures with credential rotation, and least-privilege roles so competitors cannot view sensitive operational data.
- Oracle and contract risk: anomaly detection and cross-checks against sensor spoofing; audited libraries, checks-effects-interactions patterns, pause controls, and multisignature administration.
- Privacy: keep PII and precise commercial data off-chain; use salted commitments or selective disclosure for sensitive attributes.

7. Experimental Design

A pilot can use a perishable-produce setting with one or more farms, refrigerated/insulated vehicles, and direct delivery customers, comparing HPSO-GA against standalone GA, standalone PSO, ACO, and a manual/shortest-distance baseline. The blockchain component should also be compared against a centralized audit log for verification time and tamper-evidence.

Table 3. Evaluation metrics, definitions, and expected direction of effect.

Metric	Definition	Expected effect
Transportation cost	Fuel, labor, toll, and vehicle-use cost per completed delivery plan.	Lower, via improved routing and vehicle assignment
Delivery time	Route duration and on-time delivery rate.	Lower duration; higher on-time rate
Spoilage exposure	Time-temperature violations and estimated quality-loss cost.	Lower, via perishable-aware routing and alerts
Traceability completeness	Share of required lifecycle events linked to each batch.	Higher, via mandatory contract events
Verification time	Time required to retrieve and validate batch history.	Lower, via indexed, hash-linked evidence
Settlement latency	Time from accepted delivery to payment release.	Lower, via escrow automation
Blockchain cost	Gas or transaction fee per batch lifecycle and delivery.	Controlled, via batching and off-chain storage

Table 4 lists illustrative HPSO-GA parameters a pilot study should report explicitly (with its own tuned values), alongside dataset, hardware, and random-seed details.

Table 4. Illustrative HPSO-GA parameter settings to be reported for reproducibility.

Parameter	Illustrative value	Notes
Population size	50–100	Larger populations trade runtime for search breadth
Maximum iterations	100–150	Stopping budget or convergence threshold
GA interval	Every 5–10 iterations	Frequency of selection / crossover / mutation
Crossover / mutation rate	0.7–0.9 / 0.05–0.15	Route-preserving crossover; swap or segment-reversal mutation

Parameter	Illustrative value	Notes
Inertia / cognitive / social weights	Standard discrete-PSO ranges	Tuned per problem instance
Objective weights (w_1–w_5)	Stakeholder-defined	Or replace with Pareto-ranking (Section 4)
Random seeds	≥ 10 independent runs	For statistically appropriate comparison

8. Illustrative Results Template

The values and charts below are illustrative placeholders, not measured results — replace them with output from a reproducible dataset, implementation, and protocol following Table 4.

Table 5. Illustrative comparison across methods (placeholder values).

Method	Cost index (lower)	Delivery-time index (lower)	Spoilage-risk index (lower)	Runtime (s)
Manual / shortest-distance baseline	100.0	100.0	100.0	< 1
GA	92.4	94.1	84.7	42.5
PSO	89.8	91.7	79.5	38.2
ACO	88.1	90.4	75.8	67.8
HPSO-GA (illustrative)	85.3	87.6	69.5	45.6

Figure 4. Illustrative comparison of cost, delivery-time, and spoilage-risk indices across routing methods (lower is better).

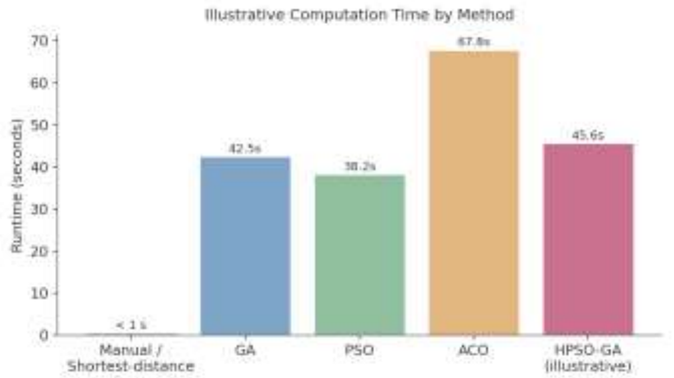

Figure 5. Illustrative computation time by method.

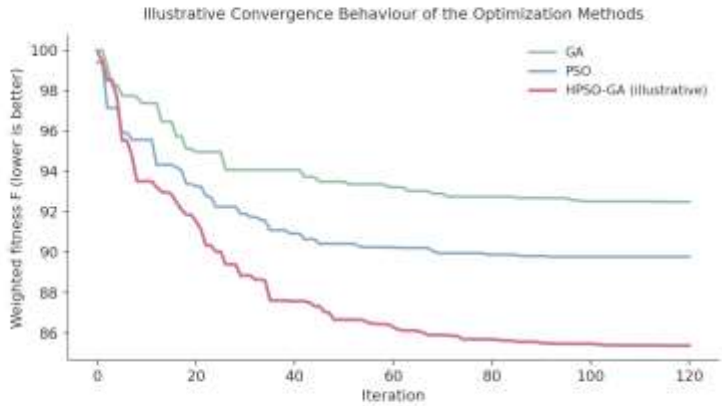

Figure 6. Illustrative convergence behaviour: weighted fitness F versus iteration for GA, PSO, and HPSO-GA.

The idea here is that the hybrid approach could incur some extra processing time, but reap benefits in terms of better routes and reduced risk of perishability. The actual superiority has to be proven through repeated runs, controlled random seeds and suitable comparison tests, reporting parameters per Table 4 with transparency and using statistical tests appropriate for the test.

9. Discussion

The framework's main value is not simply using blockchain or metaheuristics, but connecting operational optimization with accountable execution: a route plan is optimized, committed as a verifiable artifact, monitored via sensor evidence, and linked to automated payment — closing the gap between planning, execution, and settlement (Section 2).

9.1 Limitations and Threats to Validity

Some benefits of permissioned/hybrid deployments include: deployment limitations such as unreliable rural connectivity and inaccurate or manipulated sensor readings can be addressed, variable public-chain fees, and agreement on quality thresholds and dispute governance. Because Section 8 is illustrative, not measured, its indices should not be interpreted as evidence of superiority; a future empirical study would require care in avoiding instance-selection bias, parameter-tuning effort differences across the baselines, and lack of external validity due to a single pilot region, but with reporting of confidence intervals over multiple seeds and disclosure of all parameters (as in Table 4).

10. Conclusion and Future Work

While using HPSO-GA for efficient route optimization, IoT for condition monitoring, and blockchain smart contracts for secure farmer-to-consumer transportation, this paper also introduced off-chain evidence storage to maintain payments security without the need to store all the operational data on-chain, while ensuring traceability and auditable farmer-to-consumer transportation lifecycle management.

For future work, field pilots with farmer groups and logistics providers are needed, along with demand and traffic forecasting, an evaluation of outage and sensor attack resilience, and a testing of dispute and upgrade governance with reporting of operational savings, food-loss outcomes, adoption, and total cost of ownership, replacing the illustrative values in Section 8 with measured, statistically validated findings.

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