Cold-Chain Logistics Optimization for Fresh Horticultural Produce: Evidence, Models, Trade-offs, and Implementation Priorities

Faizan Tanvir*[1], Asia Laitf Mughal[1], Rimsha Shabbir [1]

[1] Institute of Food and Nutritional Sciences, Pir Mehr Ali Shah Arid Agriculture University, Rawalpindi, Pakistan

***Corresponding author:** faizantanvir344@gmail.com

Received: 21 May 2026 **Accepted**: 25 Jun 2026 **Published**: 29 July 2026

Abstract

Cold-chain failures accelerate water loss, respiration, senescence, physiological injury, and microbial spoilage in fresh fruits and vegetables, but the reported outcome depends on the endpoint and supply chain boundary. This structured narrative review asks how physical controls, digital tools, and optimization models should be selected when biological fit, measured loss and quality, food safety, cost, energy, infrastructure, and evidence readiness are considered together. Searches of scholarly and institutional sources were updated to 22 July 2026. Primary experiments, field deployments, optimization studies, reviews, and authoritative reports were classified by design, validation scale, and endpoint; a 32 record analytic inventory is supplied separately. Evidence indicates that commodity appropriate removal of field heat, stable storage and transport conditions, airflow management, suitable relative humidity, hygienic handling, and compatible packaging remain the control foundation. Sensors, radio frequency identification, block chain, and digital twins provide different information functions; none directly controls temperature or establishes microbiological safety. Optimization models can clarify trade-offs among cost, delivery time, deterioration, service, and emissions, but most evidence remains simulation or case based and rarely verifies realized food loss in commercial operation. The proposed readiness matrix links loss mechanisms and interventions to data needs, decision ownership, resource context, and accountable outcomes. Priorities are field trials, product temperature monitoring, explicit uncertainty and quality decay models, validated escalation procedures, transparent lifecycle and financial boundaries, and baselines reported with units. Investment should progress from reliable biological and operational control to monitoring, prediction, and optimization, with adoption contingent on measured improvement over a defined comparator.

Keywords: fresh produce; postharvest loss; refrigeration; precooling; monitoring; supply chain optimization; evidence readiness

DOI: https://doi.org/10.65749/pjfs.2026.30.2.0011

1. Introduction

Reducing loss in fruit and vegetable supply chains is simultaneously a food security, nutrition, income and environmental objective. The concepts must nevertheless be kept distinct. The Food and Agriculture Organization (FAO) uses *food loss* for reductions in food quantity or quality from production up to, but not including, retail, whereas *food waste* is associated mainly with retail, food service and consumers (FAO, 2019). The FAO indicator for 2023 estimates that 13.3% of food is lost globally after harvest and before retail, but that aggregate is not a universal rate for every commodity, country or supply chain stage (FAO, 2025). The United Nations Environment Programme (UNEP) separately estimated 1.05 billion tons of consumer level food waste in 2022 (UNEP, 2024). Combining these denominators or transferring either estimate to a particular horticultural chain would be misleading.

Fresh horticultural produce warrants a dedicated synthesis because it remains biologically active after harvest. Respiration consumes substrates, transpiration removes water, ethylene can accelerate ripening or senescence, mechanical injury increases susceptibility to decay, and microorganisms exploit damaged or wet tissue. Temperature affects most of these processes, but "colder" is not always "better": chilling-sensitive tropical and subtropical commodities may develop physiological injury above their freezing point, while excessive humidity, condensation, poor sanitation or incompatible mixed loads can create other quality and safety problems (Gross et al., 2016; Onwude et al., 2020). Meat, fish and dairy have materially different deterioration pathways and hazard controls; they are therefore outside this review.

The cold chain is a sequence of linked operations rather than a single refrigerator. Harvest time and maturity, shade and field delay, precooling, grading, packaging, cold storage, loading, refrigerated transport, cross-docking and retail rotation influence the temperature history and remaining commercial life of a load. A strong downstream unit cannot fully reverse delayed precooling, freezing injury, bruising or contamination introduced upstream. Conversely, a technically efficient cold room can be uneconomic or environmentally counterproductive if it is under-utilized, poorly maintained, charged with a high-impact refrigerant, supplied by an unreliable carbon-intensive grid, or installed without a route to market (FAO and UNEP, 2022).

Recent reviews describe advances in sensing, imaging, packaging, digital twins and cold-chain management (Onwude et al., 2020; Han et al., 2021; Mustafa et al., 2024), while the optimization literature has expanded rapidly across facility location, inventory, production, routing and energy decisions (Iyer and Robb, 2025). However, three interpretive errors remain common. First, a sensor that detects an excursion is treated as if it prevented loss. Second, an objective-function improvement in a simulation is treated as realized food saved. Third, records secured by blockchain are treated as inherently accurate. Each technology occupies a different part of the causal chain and depends on calibration, data coverage, decision rules, personnel and feasible corrective action.

This review narrows the topic to whole and minimally processed fresh fruits and vegetables from harvest through distribution and retail entry. It covers established physical interventions (precooling, storage, transport and modified-atmosphere packaging), information tools (sensors, Internet of Things [IoT], identification, traceability, prediction and digital twins), logistics

DOI: https://doi.org/10.65749/pjfs.2026.30.2.0011

optimization, sustainability, economics and end-of-life routing. The principal outcome is not a single pooled effect; it is a decision framework that asks whether an intervention is biologically appropriate, operationally feasible, supported by evidence at the claimed scale, and linked to an accountable endpoint.

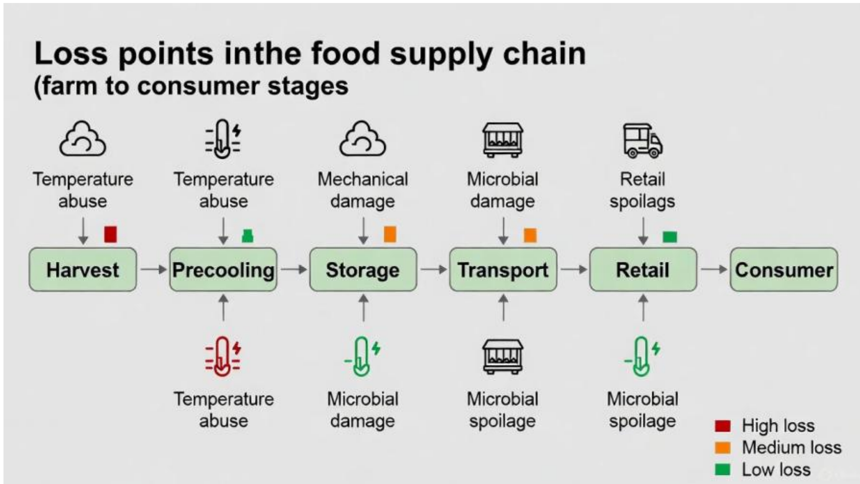

Figure 1: Loss points in the food supply chain (Farm to consumer stage)

The research question is: How should cold-chain interventions and optimization models be selected for fresh horticultural produce when biological fit, food safety, measured physical and quality loss, cost, energy, infrastructure and evidence readiness are considered together? The novelty is an evidence- and readiness-based synthesis that connects the loss mechanism and commodity to the control action, data architecture, model, trade-offs, validation scale and adoption gate.

2. Review approach and evidence classification

2.1 Search scope and source selection

This review was conducted as a structured narrative review rather than a systematic review or meta-analysis. Targeted searches were updated to 22 July 2026 using PubMed, Google Scholar, ScienceDirect, publisher platforms and institutional repositories. Search concepts were combined in groups: ("fresh produce" OR fruit OR vegetable OR horticultural) AND ("cold chain" OR precooling OR refrigerated transport OR cold storage OR "modified atmosphere") AND (loss OR quality OR shelf life OR safety); and ("cold chain" OR perishable) AND (optimization OR routing OR network OR inventory OR "quality decay" OR "digital twin" OR IoT OR sensor OR blockchain). Backward and forward citation checks were used for foundational studies and corrected records identified during the claim-to-source audit.

English-language peer-reviewed articles, authoritative reports and technical handbooks were eligible. The principal date window was 2014-22 July 2026, with earlier sources retained when they defined a method, postharvest requirement or optimization formulation still used in the recent literature. Sources were included when they specified a relevant commodity or fresh produce

DOI: https://doi.org/10.65749/pjfs.2026.30.2.0011

context, cold-chain stage, intervention or model, and at least one interpretable outcome or decision variable. Sources were excluded when they concerned only meat, fish, dairy or pharmaceuticals; ambient processing unrelated to a cold chain; consumer waste without a postharvest logistics link; or asserted a performance benefit without enough methodological information to interpret the claim.

Because the review was developed iteratively and was not based on a prospective protocol or a single exported bibliographic database, candidate identification and exclusion counts were not retained. Inventing a PRISMA-style flow would be inappropriate. Instead, the final analytic inventory is made auditable: the supplementary table lists 32 core records by source type, commodity/context, scale, intervention or model, comparator, measured endpoint and limitation. Authoritative sources used only to define food loss/waste or commodity storage guidance are identified separately in the reference list. This transparent limitation means the review should be interpreted as a critical, decision-oriented synthesis, not an exhaustive prevalence estimate.

2.2 Evidence categories and readiness

Evidence was classified before claims were synthesized, which includes institutional indicators, handbooks and standards that define boundaries or recommended conditions. Review which includes narrative, scoping or systematic synthesis; useful for breadth but not direct evidence that an intervention caused an outcome. Laboratory or pilot experiment for controlled product or package evaluation, usually with defined temperatures and quality measurements but limited logistics complexity. Commercial field deployment or observational study for technology operated in a working chain; may demonstrate feasibility and exposure detection but needs a comparator to attribute loss reduction. Optimization model or simulation having mathematical formulation evaluated with synthetic, benchmark or case data; supports prospective decisions but does not alone demonstrate food saved. Conceptual framework, interview or implementation case identifies mechanisms, opportunities and constraints; causal performance claims require separate outcome evidence.

Four readiness levels are used in the synthesis: R1, conceptual (function and proposed mechanism); R2, laboratory or simulation validated; R3, pilot or case validated in a relevant operational setting; and R4, replicated commercial outcome evidence with a defined comparator and implementation conditions. Readiness is assigned to the specific claimed use, not to the technology name. For example, temperature sensing is mature for measurement, but a sensor driven shelf life decision may be only R2 or R3 if the quality model and escalation protocol have not been validated for the commodity and route.

2.3 Outcome definitions and causal language

The review uses the following endpoints which includes Physical loss, mass or units removed from the food supply chain, reported against a stated denominator. Quality loss, change in market or sensory attributes such as firmness, color, flavor, turgor or visible defects; market rejection is reported separately because grading rules vary. Nutritional deterioration, measured change in nutrients or bioactive compounds, not inferred from appearance alone.

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Safety non-compliance includes failure of a validated hazard-specific microbiological, chemical or physical criterion. Temperature history can inform risk but does not prove safety. Shelf life is the time to a prespecified quality or safety limit under stated conditions; an extension is meaningful only relative to a comparator and endpoint. Economic loss is reduction in saleable yield, revenue or margin, or additional cost; price and quantity components should be separated.

Terms such as demonstrated, reduced or improved are reserved for studies that measured the relevant outcome against a comparator. Detected, predicted, optimized and proposed describe monitoring, modeling and conceptual findings without implying realized loss prevention.

3. Biological and measurement basis for cold-chain decisions

3.1 Commodity, maturity and initial condition

Cold-chain design begins with the product, not the device. Cultivar, maturity at harvest, preharvest weather, field temperature, size, surface-to-volume ratio, respiration rate, ethylene sensitivity and mechanical damage affect cooling and deterioration. A route that is suitable for mature green tomatoes is not automatically suitable for berries, leafy vegetables or chilling-sensitive mangoes. Target temperature and relative humidity should therefore be drawn from commodity-specific guidance and validated against the intended market duration (Gross et al., 2016).

Initial load temperature is particularly important. The refrigeration demand required to remove field heat can exceed the heat entering later through insulation, doors and respiration. Delayed precooling can consume a substantial portion of remaining commercial life, whereas loading warm produce into a vehicle intended only to maintain temperature may create slow and spatially uneven pull down. Reporting only the thermostat set-point conceals this difference.

3.2 Heat, moisture, gases and microbial hazards

The time–temperature history affects respiration, senescence and growth of spoilage organisms, but air and product temperatures are not interchangeable. Air may respond quickly to compressor cycles and door openings while the product core changes slowly. Sensor position near an evaporator, ceiling or door can therefore misrepresent the warmest or slowest cooling part of a pallet. Studies and audits should report sensor accuracy, calibration, location, sampling interval, missing data and whether product, pulp, surface or air temperature was measured (Mercier et al., 2017; Badia-Melis et al., 2018).

Relative humidity is similarly double-edged. High humidity limits water loss and wilting, but surface condensation can promote decay, weaken cartons and transfer microorganisms. Airflow must remove heat without creating excessive dehydration; package vents and pallet stacking must match the cooling method. Respiration also produces heat and carbon dioxide, and mixed loads may expose ethylene sensitive commodities to ethylene-producing fruit. The appropriate control is consequently a combination of temperature, humidity, airflow, gas exchange, hygiene and compatibility.

Food safety and quality must remain separate. Cooling generally slows microbial growth but does not sanitize contaminated produce. Hydrocooling and flume water can spread contamination if

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disinfectant concentration, organic load, temperature and water replacement are not controlled. Modified atmospheres can slow respiration, yet excessively low oxygen or high carbon dioxide can cause anaerobic metabolism, off-flavors or tissue injury. No temperature excursion algorithm should be used to release a load as “safe” without a validated hazard model and the relevant process controls.

4. Physical interventions: the control foundation

4.1 Precooling and first-mile handling

Precooling removes field heat soon after harvest using room cooling, forced-air cooling, hydrocooling, vacuum cooling, package icing or combinations. Selection depends on commodity tolerance to water and vacuum, package ventilation, throughput, water quality, energy and capital. Forced-air systems can improve cooling uniformity when vents align and air bypass is controlled; hydrocooling is rapid for water tolerant produce but requires hygienic water management; vacuum cooling is effective for high surface area leafy vegetables but has product and equipment constraints (Duan et al., 2020).

Cooling performance should be expressed as product temperature pull down for example, time to seven-eighths cooling rather than only room set point. Minimum reporting includes cultivar and maturity, harvest and load temperature, target temperature, cooling medium, air or water flow, package and stacking, mass, cooling time, energy use and quality outcome after the intended distribution period. Without these data, a “precooled” treatment cannot be reproduced or compared.

Low-resource chains may benefit more from shade, shorter field delay, ventilated crates, coordinated pickup and a correctly sized shared precooler than from an advanced analytics platform. The decision criterion is avoided deterioration per unit of total cost and energy under realistic throughput, not technological novelty.

4.2 Storage and transport

Cold stores and vehicles must maintain a commodity appropriate envelope while allowing heat removal and air circulation. Important design and operating variables include insulation, refrigeration capacity at local ambient conditions, evaporator and fan configuration, defrost, door discipline, pallet spacing, return air paths, loading density, preventive maintenance, backup power and refrigerant leakage. A set point is not evidence that the load stayed within specification.

Temperature heterogeneity is a persistent problem. Reviews document spatial differences within rooms, containers, pallets and packages, with consequences for residual shelf life (Jedermann et al., 2014, 2017; Badia-Melis et al., 2018). Validation therefore requires temperature mapping under representative loads and seasons, followed by risk-based sensor placement. The warmest location is not necessarily fixed; door operations, airflow obstruction and mixed loads can shift it.

Transport planning must incorporate the fact that many refrigerated vehicles are designed to maintain, not rapidly reduce, product temperature. Pre-trip inspection, equipment pull-down, verified product temperature before loading, airflow channels, door-opening control and response

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procedures are operational prerequisites. Time–temperature abuse is a cumulative exposure problem, but the biological response is commodity and hazard-specific; simple “minutes out of range” rules may be too crude (Ndraha et al., 2018).

4.3 Modified and controlled atmospheres

Modified-atmosphere packaging (MAP) alters oxygen, carbon dioxide and water-vapor conditions through film permeability, produce respiration, package geometry, temperature and initial gas composition. A successful design must match respiration over the full anticipated temperature range. A package optimized at stable refrigeration can become oxygen-limited during an excursion because respiration increases more rapidly than gas transmission.

Controlled studies show that packaging and atmosphere can slow selected quality changes for specific produce. For example, a consolidated cold-chain and modified-atmosphere system was evaluated for strawberries under defined supply-chain conditions (Zhao et al., 2019), and dynamic controlled atmospheres have been studied for apple quality (Mditshwa et al., 2018). These results cannot be generalized without the commodity, cultivar, maturity, film, gas, temperature, relative humidity and endpoint. Microbial consequences must also be evaluated: suppressing visible spoilage is not equivalent to controlling pathogens (Sandhya, 2010; Caleb et al., 2013). Representative evidence and the limit of each supported claim are compared in Table 1.

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Table 1. Representative evidence and the limit of the supported claim

Source and design	Commodity/context	Intervention or tool	Comparator and endpoint	Supported inference	Readiness / main limitation
Duan et al. (2020)	Fruits and vegetables	Precooling methods	Cooling rate, method fit and quality across published studies	Rapid removal of field heat is foundational; method must match commodity and package	R3–R4 for established methods; heterogeneous reporting and economics
Zhao et al. (2019)	Strawberry	Refrigeration plus MAP	Defined package/cold-chain treatments; quality and shelf-life measures	Combined atmosphere and temperature control can retain strawberry quality under studied conditions	R2; cultivar, package and route specificity
Lamberty and Kreyenschmiet al. (2022)	Fresh fruit and vegetables	IoT-enabled ambient monitoring	Temperature and logistics data during supply-chain use	Feasibility of real-time condition visibility	R3 for monitoring; no controlled food-loss endpoint
Gillespie et al. (2023)	Refrigerated deliveries	IoT anomaly detection and alerts	Detection/notification performance during transport	Anomalies can be detected and communicated in a small fleet	R3 for alerts; not evidence of quantified spoilage reduction
Torres-Sánchez et al. (2020)	Fruit and vegetables	Real-time monitoring and shelf-life estimation	Sensor inputs and estimated remaining life	Temperature histories can support modeled shelf-life decisions	R2–R3; model validity is commodity- and endpoint-dependent
Defraeye et al. (2021)	Postharvest supply chains	Digital twins	Published models and prospective applications	Digital twins can integrate measurements and models for prediction	R1–R2 for most uses; validation, uncertainty and transferability gaps

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Kayikci et al. (2022)	Food supply chains/emerging economies	Blockchain framework	People, process, performance and technology barriers	Blockchain may improve agreed-record traceability when governance is present	R1–R3 for traceability; oracle, interoperability and adoption constraints

The pathway from exposure measurement to corrective action and accountable outcomes is summarized in Fig. 1.

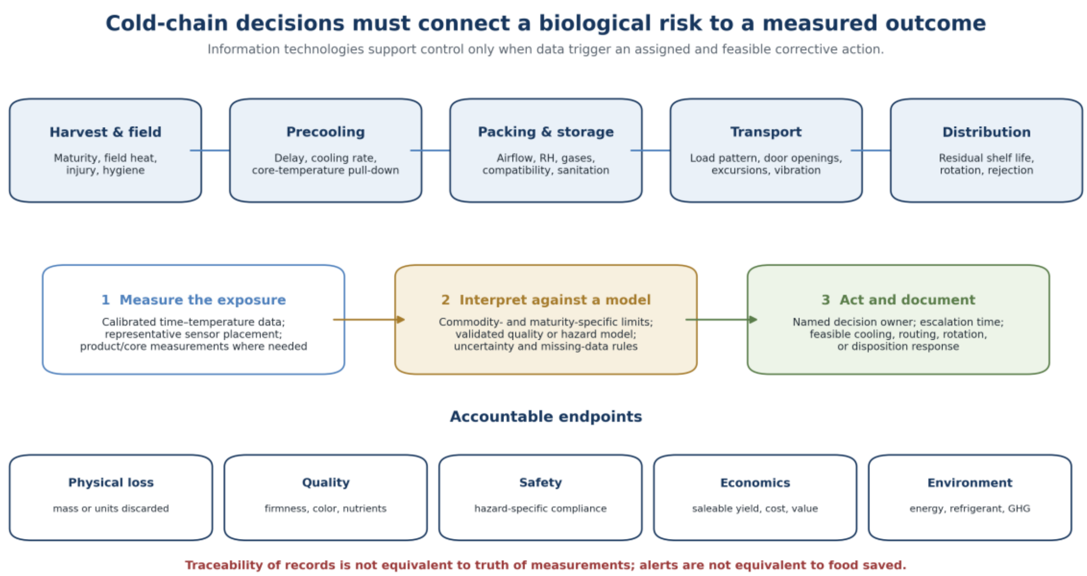

Figure 2: Cold-chain decision pathway linking supply-chain stage, measurement, interpretation, corrective action and accountable endpoints

5. Digital monitoring, traceability and prediction

5.1 Sensors and IoT: measurement before analytics

Sensors and IoT platforms can increase visibility by collecting temperature, humidity, gas, location, shock or door-status data and communicating alerts (Ben-Daya et al., 2021). Their value depends on metrological and operational details often omitted from high-level discussions. Minimum specifications include accuracy over the relevant range, calibration traceability and interval, drift, response time, resolution, sampling frequency, clock synchronization, ingress protection, battery life, memory, transmission coverage and data-recovery behavior. Installation should be validated after cleaning, maintenance or load-pattern changes.

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Placement is an inference problem. A single wall sensor can describe equipment control but not the distribution of product exposure. Pallet level sensors improve spatial resolution yet still may miss hot spots or core temperatures. A risk-based design maps the chamber or route, selects sentinel locations, and states what population the readings represent. Missing data, delayed transmission, false alerts and alert fatigue require explicit rules. The receiving operator needs an escalation window and feasible response repair, reicing, rerouting, accelerated rotation, segregated inspection or disposition, otherwise real time data become retrospective documentation.

The distinction between monitoring and outcome is illustrated by Gillespie et al. (2023): the study demonstrated real-time anomaly detection and notification in three delivery vans. It supports feasibility of small-fleet monitoring and alerts, not a quantified reduction in spoilage. Similarly, remote cold-store systems can demonstrate environmental visibility (Afreen and Bajwa, 2021), but food saved must be measured with a comparator, denominator and time horizon.

5.2 Identification, sensing and trustworthy traceability

Radio-frequency identification (RFID) is primarily an identification and data-link technology; some tags incorporate sensors, but an identity tag alone does not measure temperature. Traceability architecture must define identifiers for lots, packages, pallets and locations; event semantics; time synchronization; chain of custody; data retention; and integration with inventory, quality and food safety systems. Interoperability failures can create complete records within one organization and gaps at handovers.

Blockchain can make agreed records difficult to alter after entry, but cannot verify the truth of a sensor, manual observation or certificate at the moment of entry. This is the “oracle” problem. Governance questions include who can write and correct data, how commercial confidentiality is protected, which events are mandatory, how sensor identities and calibrations are authenticated, how off-chain data are retained, and who bears cyber and recovery costs. Reviews and implementation interviews show both traceability opportunities and people/process impediments (Kamilaris et al., 2019; Kayikci et al., 2022). The supported conclusion is conditional: distributed ledgers may strengthen traceability when data governance and interoperable processes are already credible.

5.3 Prediction, AI and digital twins

A shelf-life model maps exposure and product attributes to a defined quality or safety endpoint. Required inputs may include time–temperature history, gas composition, humidity, maturity, initial quality, microbial status or handling events. Model performance should be reported on independent data from representative seasons, cultivars and routes, with calibration and discrimination metrics, uncertainty intervals and failure conditions. A black-box prediction without external validation can rank loads incorrectly when the operating distribution changes.

Digital twins extend this idea by maintaining a virtual representation of a product, package, load, equipment item or network. They can combine sensors with heat-transfer, airflow, respiration, quality-decay or logistics models to estimate unmeasured states and evaluate alternatives (Defraeye et al., 2021). Yet the twin inherits error from sensors, boundary conditions, model structure and updating rules. A high-resolution visualization is not evidence of high predictive

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validity. Deployment therefore requires version control, uncertainty propagation, explainable decision thresholds, cybersecurity and a process for retiring a model that no longer performs.

6. Optimization as a decision discipline

6.1 Formulation classes are not solution methods

Optimization selects decisions that improve one or more objectives subject to constraints. Facility location, capacity, production, inventory, allocation, routing, scheduling, temperature set-points, packaging and product disposition can be modeled at strategic, tactical or operational horizons. A linear or mixed integer formulation describes relationships among variables; stochastic, robust or fuzzy approaches represent different kinds of uncertainty. Genetic algorithms, ant colony methods, tabu search and non-dominated sorting are solution methods. Treating "fuzzy," "genetic" and "multi-objective" as equivalent optimization types obscures what decision is being made and what is guaranteed.

A reproducible model report should specify commodity and biological assumptions; geography and network; time horizon; decision variables; objectives with units; constraints; temperature or quality-decay function; uncertainty distribution or ambiguity set; data source; solver or algorithm, settings and stopping rule; instance size and computing time; baseline; sensitivity or stress tests; and validation. For multi-objective models, a single weighted sum can hide trade-offs. Pareto-efficient alternatives and the consequence of changing weights are more informative to decision-makers.

6.2 Deterioration and uncertainty

Perishability is sometimes represented only by a fixed shelf-life constraint. More informative models connect quality to time and temperature, allow heterogeneous initial quality, and restrict service or acceptance by remaining shelf life. Rong et al. (2011) integrated product quality in production and distribution decisions, while de Keizer et al. (2017) modeled heterogeneous quality decay in perishable logistics network design. Such formulations improve biological relevance but depend on the validity of decay parameters and the availability of initial-condition data.

Uncertainty arises from demand, travel time, ambient conditions, equipment failure, harvest volume and quality, energy prices and market acceptance. Scenario-based stochastic programming is appropriate when defensible probabilities exist; robust optimization protects against a defined uncertainty set; fuzzy models can represent imprecise preferences or parameters but should not substitute for missing empirical data. Every approach should report the price of robustness or recourse and compare against a deterministic baseline.

6.3 What the current model evidence supports

Bortolini et al. (2016) formulated a three-objective fresh-food distribution problem spanning cost, delivery time and carbon footprint. It demonstrates how conflicting objectives can be made explicit. Wang et al. (2021) considered collaborative distribution centers, resource sharing and temperature-control constraints in a bi-objective mixed-integer model, using a hybrid clustering/metaheuristic procedure and case/benchmark evaluation. Mejjaouli and Babiceanu

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(2018) developed a real-time rerouting architecture for cold supply chains. These studies support model feasibility and prospective improvements relative to their selected baselines; they do not establish that the same percentages will occur in another country, commodity, fleet or commercial season.

The recent systematic review by Iyer and Robb (2025) mapped 234 cold-chain optimization publications and found a broad, growing literature. Its breadth strengthens the case for optimization as an analytical core, while also exposing fragmentation in objectives, data and validation. The evidence gap is no longer a lack of algorithms; it is the limited transition from formulation and simulation to transparent, independently evaluated operational use.

Representative optimization studies and the conditions required for interpreting their results are compared in Table 2.

Table 2. Reporting and validation of representative optimization studies

Source	Problem / formulation	Decisions and objectives	Deterioration / uncertainty	Solution and validation	Transfer limitation
Rong et al. (2011)	Integrated production–distribution model	Production and distribution decisions; cost with product quality	Time/temperature-related quality considerations	Mathematical optimization with illustrative/case evaluation	Quality parameters and network assumptions require local validation
Bortolini et al. (2016)	Three-objective fresh-food distribution	Minimize cost, delivery time and carbon footprint	Perishability /time constraints; scenario-specific inputs	Multi-objective analysis with case application	Environmental result depends on boundary, fleet and demand data
de Keizer et al. (2017)	Perishable logistics network design	Facility/network flows, cost and delivered quality	Heterogeneous quality decay	Optimization with numerical/case analysis and sensitivity	Model quality depends on initial-quality and decay estimates
Mejjaouli and Babiceanu (2018)	Real-time cold-chain rerouting	Routing response to monitored conditions; logistics performance	Dynamic conditions and event data	System architecture and computational/case evaluation	Operational latency, communications and food outcome need field confirmation

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Wang et al. (2021)	Bi-objective collaborative distribution network	Resource sharing, centers/routes, cost and vehicle use	Temperature-control constraints; case parameters	MILP; clustering plus TS–NSGA-II; Chongqing case and benchmarks	Metaheuristic solutions and case data do not guarantee external performance
Wang et al. (2024)	Data-supported cold-chain cost optimization	System cost decisions using clustered data	Dataset-dependent representation	Four simulated datasets and one real dataset; computational comparison	Field loss, quality and implementation outcomes were not established
Iyer and Robb (2025)	Systematic review of optimization models	Taxonomy across cold-chain decisions and objectives	Maps treatment across 234 publications	Systematic literature synthesis	Review-level evidence; study quality and validation remain heterogeneous

These reporting requirements are organized as a staged validation pathway in Fig. 3.

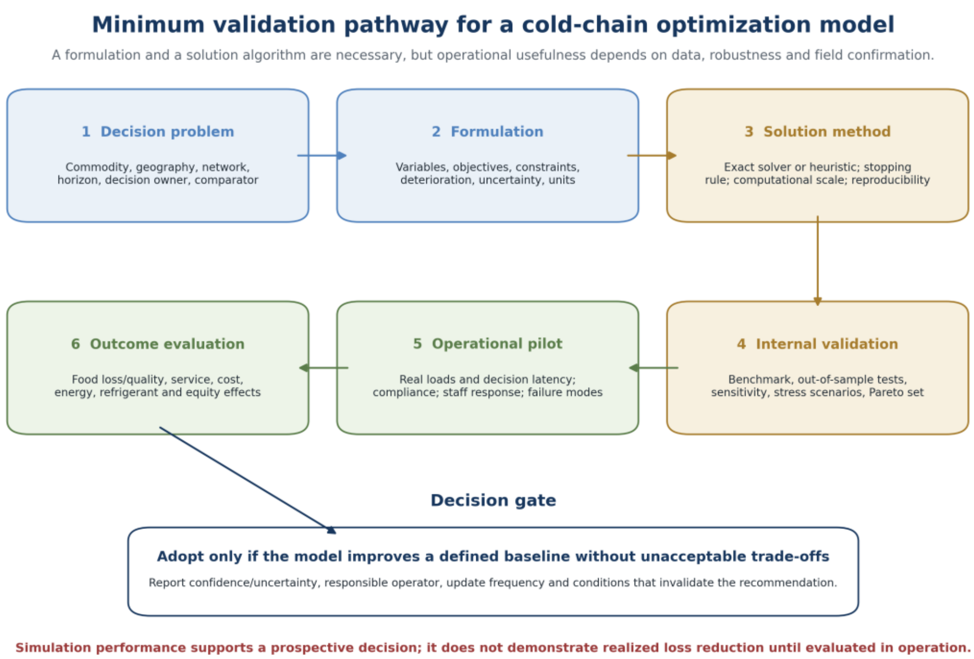

Figure 2: Minimum validation pathway for cold-chain optimization

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7. Sustainability, economics and infrastructure

7.1 Evaluate food saved and the burden of saving it

Cooling can avoid the upstream environmental burdens embodied in lost produce, but refrigeration also consumes energy, can leak high-global-warming-potential refrigerants, requires equipment and packaging, and may shift demand to a carbon-intensive grid (James and James, 2010; FAO and UNEP, 2022). The correct environmental question is not whether cooling uses energy; it is whether the intervention reduces total impact relative to a specified baseline for the same delivered function.

Life-cycle assessment should state the functional unit (for example, one kilogram of acceptable produce delivered at retail entry), system boundary, geography, season, baseline chain, grid mix, refrigeration efficiency, refrigerant type and leakage, equipment utilization and lifetime, packaging, water use, avoided loss rate and end-of-life treatment. Read et al. (2020) showed through an environmentally extended input–output analysis that the benefit of reducing food loss and waste varies by commodity, stage and impact category. Therefore, a universal statement that an intervention cuts energy or emissions by a fixed percentage is not defensible.

Sensitivity analysis is essential because modest changes in assumed avoided loss, throughput, grid carbon intensity or leakage can change the result. Rebound should also be considered: lower unit cost or longer shelf life may increase volumes, distance or inventory and offset part of the gain.

7.2 Financial viability and equitable access

A technically effective intervention can fail if cash flow, utilization or service arrangements are weak. Financial assessment should separate capital expenditure, installation, land and grid connection from electricity or fuel, labor, calibration, data subscription, refrigerant, packaging, sanitation, maintenance, spare parts and downtime. The relevant denominator may be crates or tonnes processed, saleable kilograms delivered, or avoided rejection not nominal equipment capacity.

For shared infrastructure, the business case depends on seasonal throughput, scheduling among growers, payment collection, product aggregation and assured market access. Smallholders may face barriers even where total-chain savings are positive because costs and benefits accrue to different actors. Contracts, cooperatives, pay-per-crate services, leasing, concessional finance, insurance and public private facilities can redistribute risk, but require transparent service levels and governance.

Skills and spares are part of the technology. A minimum implementation plan covers operator training, preventive maintenance, calibration, sanitation, emergency procedures, backup power, refrigerant service, data ownership and vendor exit. In unreliable-grid contexts, passive insulation, evaporative cooling where climatically suitable, thermal storage, solar-assisted systems and coordinated daytime precooling may be more robust than an oversized conventional plant. Options should be compared on delivered service, not equipment label.

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7.3 Readiness-based adoption matrix

The resulting evidence- and readiness-based adoption gates are summarized in Table 3.

Table 3. Evidence- and readiness-based implementation matrix

Intervention	Best-fit problem	Minimum data and controls	Evidence readiness	Main failure mode	Adoption gate
Shade, shorter field delay, gentle handling	Field heat, water loss, bruising	Harvest time, initial temperature, delay, injury/rejection	R4 in principle; local outcome varies	No coordination or containers that cause injury	Measured reduction in delay/injury against current practice
Commodity-matched precooling	High field heat and rapid deterioration	Initial/core temperature, target, pull-down time, package/airflow, hygiene	R3–R4	Method–commodity mismatch, slow/uneven cooling, contaminated water	Reproducible core-temperature pull-down and quality benefit at viable throughput
Cold storage and refrigerated transport	Maintain condition after cooling	Temperature map, product temperature, capacity, airflow, maintenance, backup	R4 for basic control; route-specific design	Warm loading, blocked airflow, doors, outages, leakage	Stable product exposure plus saleable-yield/service improvement
MAP / controlled atmosphere	Respiration, moisture and gas management	Commodity/cultivar, maturity, respiration, film permeability, gas/RH, temperature	R2–R3 for many applications	Anaerobiosis, condensation, injury or microbial misconception	Quality endpoint improved without safety or sensory penalty under excursion tests
IoT condition monitoring	Invisible excursions and delayed response	Calibrated sensors, representative placement, connectivity, alert ownership	R3 for monitoring	Drift, missing data, false alerts, no feasible action	Alerts are timely, acted upon and linked prospectively to a measured endpoint

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RFID / blockchain traceability	Lot identity and fragmented records	Data standards, identity, custody, permissions, correction and audit rules	R2–R3 for traceability	"Garbage in, immutable garbage out"; interoperability/cost	Faster or more complete traceability against baseline with verified data governance
Shelf-life model / digital twin	Rotation, routing and scenario testing	Initial quality, exposure data, validated model, uncertainty and update rules	R1–R3	Dataset shift, unvalidated endpoint, false precision	Independent validation and decision benefit exceeding error/cost
Network, inventory or routing optimization	Multi-actor trade-offs and constrained resources	Audited demand, time, cost, capacity, quality-decay and uncertainty data	R2; limited R3–R4 outcome evidence	Unrealistic parameters, opaque weights, no operational ownership	Better baseline performance in stress tests followed by a monitored field pilot

8. Prevention, redistribution and circular routing

Circular-economy language can obscure the priority of preventing edible food from becoming surplus or waste. A food-use hierarchy places prevention first, followed by redistribution for human consumption where quality, safety and logistics permit; conversion to animal feed under applicable controls; material or biochemical valorization; energy recovery; composting; and disposal (Papargyropoulou et al., 2014; Teigiserova et al., 2020). These pathways are not environmentally or nutritionally equivalent.

Cold-chain information can support earlier rotation, transfer or donation by estimating remaining quality life, but dynamic discounting or redistribution must not pressure staff to sell or donate unsafe food. Disposition rules should use validated criteria, preserve traceability and identify who accepts liability and transport cost. Product rejected for cosmetic quality may be suitable for another human-food outlet; product with uncertain contamination or temperature history may not be.

Valorization decisions require mass balance, safety, market demand and life-cycle assessment. A technically feasible extract, feed or bioenergy pathway may consume more energy, water or chemicals than a simpler route, or may depend on a seasonal feedstock too variable for reliable operation. Optimization of reverse flows should therefore report the amount and condition of material, distance, yield, displaced product, processing burden and final market—not simply "waste minimized."

DOI: https://doi.org/10.65749/pjfs.2026.30.2.0011

9. Comparative synthesis and decision framework

The evidence supports a staged investment logic. Firstly, stabilize biological and operational control. Specify commodity, maturity, intended market life and acceptance endpoint. Reduce field delay and injury; match precooling to the product and package; verify core pull-down; map storage and transport; maintain hygiene, airflow and equipment; and assign operational responsibility. Secondly, instrument the highest-consequence uncertainties includes selection of sensors and sampling frequency from a decision need rather than a desire for data volume. Map heterogeneity before choosing locations. Establish calibration, missing-data and escalation procedures, and verify that the responsible person can act within the remaining response window.

Thirdly we validate and interpret the data. Connect exposures to commodity-specific quality or hazard models. Report uncertainty, independent validation and conditions that invalidate the model. Identification and traceability data should be interoperable and governed, with clear custody and correction rights. Fourth, optimize defined decisions. Build a baseline and specify variables, objectives, constraints and units. Include quality decay or remaining shelf life where it changes decisions. Compare exact and heuristic solutions appropriately, report computational scale and sensitivity, and show Pareto trade-offs rather than hiding them in unexamined weights.

Fifth, verify outcomes in operation. A monitored pilot should measure physical or quality loss, service, cost, energy and unintended effects against the current practice over enough loads and seasons to expose failure modes. The model or technology should be revised or withdrawn if performance shifts outside the validated range.

This sequence does not imply that every chain requires blockchain, AI or a digital twin. A low-cost improvement in field delay or airflow may produce a larger, more certain benefit than an advanced platform. Conversely, a high-volume, multi-route chain with stable physical control and reliable data may benefit substantially from dynamic routing or shelf-life-aware inventory. Readiness is therefore a property of the technology–commodity–decision–context combination.

10. Limitations and research priorities

This review has four limitations. First, it is a structured narrative synthesis without prospective registration or retained screening counts, so selection bias and incomplete retrieval are possible. Second, terminology and endpoints vary widely; many studies report temperature, model cost or nominal shelf life rather than physical loss, saleable yield or independent safety outcomes. Third, laboratory packages, single-route pilots and modeled networks have limited external validity across cultivars, seasons, countries and infrastructure. Fourth, English-language and accessible-source restrictions may underrepresent local operational knowledge in high-loss regions.

Research should address the following priorities includes reporting of load count, mass denominator, baseline, product/core temperature, rejection, quality, safety, cost and energy over multiple seasons. Publish sensor calibration, drift, placement rationale, sampling, missingness and mapping of pallets, vehicles and rooms. Include initial quality, maturity and uncertainty; validate on independent routes and state failure boundaries. Release de-identified instances or generators, parameter sources, code or pseudocode, solver settings, stopping rules and full baseline/sensitivity results.

Move beyond simulation to prospective pilots that measure whether recommendations were implemented and whether food, cost or emissions changed. Integrate avoided food loss with electricity, fuel, refrigerant leakage, packaging, water, maintenance, capital, service and equity. Compare modular, shared and passive solutions; analyze financing, utilization, technical service, gender and bargaining effects. Validate hazard-specific decision rules and prevent quality predictions from being used as unqualified safety assurances.

11. Conclusion

Cold-chain optimization for fresh horticultural produce is not principally a contest among technologies. It is the disciplined connection of a commodity-specific deterioration mechanism to a feasible control action, a representative measurement, a validated interpretation and an accountable outcome. The strongest practical evidence supports rapid and appropriate removal of field heat, stable temperature and humidity, hygienic handling, airflow and package compatibility. These controls should be established before advanced analytics are expected to compensate for basic operational failure.

Digital monitoring can reveal excursions; RFID can identify lots; blockchain can preserve agreed records; predictive models and digital twins can estimate unmeasured states; and optimization can compare constrained alternatives. None independently guarantees temperature control, data truth, corrective action, microbiological safety or food saved. Current optimization evidence is rich in formulations and simulations but thinner in replicated commercial outcome evaluation.

Investment should therefore be gated by biological fit, data quality, operator ownership, baseline comparison, uncertainty, total cost and environmental burden. Promising tools should advance from laboratory or simulation evidence to operational pilots and then to replicated outcome studies. When studies report commodity, comparator, units, validation scale and trade-offs transparently, cold-chain optimization can become a credible route to greater saleable yield, safer decisions and lower whole-system impact rather than an unsupported technological promise.

Statements and Declarations

Ethical considerations: Ethical approval was not required because this article is a review of previously published literature and involved no new research with human participants or animals.

Data availability: No new datasets were generated. The evidence-classification data used in this review are provided in the Supplementary Study Inventory.

Funding statement: This research received no specific grant from any funding agency in the public, commercial or not-for-profit sectors.

Declaration of conflicting interest: The authors declared no potential conflicts of interest with respect to the research, authorship and/or publication of this article.

Authors' contributions: All authors contributed to the conception, literature search, evidence appraisal, synthesis, drafting and critical revision of the manuscript, and all authors approved the final version.

Acknowledgments: None.

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