Postharvest Processing and Storage Technologies for Horticultural Produce and Grains: Evidence, Trade-offs and Strategies for Loss Reduction

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Abstract

Postharvest interventions can preserve food already produced, but their performance depends on commodity physiology, initial quality, operating conditions, and supply-chain capability. This structured narrative review asks how drying, hermetic storage, pre-cooling and cold-chain management, controlled or modified atmospheres, and selected active or digital technologies should be matched to horticultural produce and grains when efficacy, quality, safety, cost, energy, and implementation constraints are considered together. Peer-reviewed and authoritative evidence published mainly from 2000 to 22 July 2026 was searched and appraised; older landmark sources were retained where they define established principles. Current global indicators show that 13.3% of food is lost between production and the stage immediately before retail, while consumer-facing waste is a separate problem. No universal loss percentage or shelf-life multiplier is supported across commodities. Drying and hermetic storage are comparatively accessible for grains, provided that safe initial moisture, package integrity, and re-opening practices are controlled. For fresh produce, rapid removal of field heat and an unbroken, commodity-specific cold chain remain the foundation; controlled atmosphere, modified atmosphere packaging, 1-methylcyclopropene, coatings, or ozone are adjuncts rather than substitutes. Nano-enabled packaging and digital twins remain conditionally promising because migration, validation, interoperability, and regulatory questions persist. Two comparative matrices translate the evidence into a selection framework. The strongest strategy is therefore not the most complex technology, but a validated system whose physiological fit, hazard controls, resource demands, and market value are aligned.

Keywords: Food loss; Postharvest; Cold chain; Hermetic storage; Modified atmosphere packaging; Drying; Technology selection

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1. Introduction

Harvest does not stop biological change. Fruit and vegetables continue to respire and transpire; many also synthesize or respond to ethylene. Grains and pulses are less metabolically active after adequate drying, but remain vulnerable to moisture migration, insects, rodents, fungi, and mechanical damage. These processes can reduce mass, nutritional or sensory quality, safety, market grade, and economic value. They are related outcomes, not interchangeable measures.

The contemporary baseline is more precise than the often-repeated claim that one third of all food is "lost after harvest." The Food and Agriculture Organization of the United Nations (FAO) estimates that 13.3% of food was lost globally in 2023 after production and before retail; the indicator varies by region and commodity group (FAO, 2026). The United Nations Environment Programme estimated 1.05 billion tonnes of food waste at retail, food-service, and household stages in 2022, including inedible parts (UNEP, 2024). These two indicators cover different supply-chain boundaries, denominators, and measurement systems. The older 1.3-billion-tonne estimate combined loss and waste across stages and should not be used as a current postharvest-loss statistic (FAO, 2019).

"Postharvest loss" is used here for a measurable reduction in the quantity, quality, safety, or economic value of crops from harvest through handling, storage, transport, processing, and wholesale, before retail. "Food loss" follows the FAO boundary from postharvest production to, but excluding, retail. "Food waste" refers to retail and consumption stages. Quantitative loss is a reduction in edible mass or count; qualitative loss includes deterioration of safety, nutrient content, sensory properties, processing functionality, or grade. Economic loss additionally depends on price, timing, and market acceptance. Shelf life is the time during which a product remains safe and acceptable under stated conditions and against defined end points. Consequently, shelf-life extension is meaningful only when the control, temperature, humidity or atmosphere, package, duration, and rejection criteria are reported.

Loss estimates are heterogeneous because field sampling, visual grading, farmer recall, mass balance, and economic valuation produce different answers. A meta-analysis of postharvest studies in sub-Saharan Africa demonstrated wide variation across commodities, stages, and measurement approaches (Affognon et al., 2015). Broad percentages detached from these

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conditions can misdirect investment. Technology assessment likewise fails when it reports a biological effect but omits energy reliability, sanitation, package integrity, operator skill, worker exposure, waste management, or market value.

This review is restricted to horticultural produce (whole and fresh-cut fruit and vegetables) and grains or pulses from harvest to pre-retail distribution. Fish, meat, dairy products, and primary crop production are outside scope. The technologies considered are drying, ambient and evaporative systems, hermetic storage, pre-cooling and cold-chain management, controlled atmosphere (CA), modified atmosphere packaging (MAP), 1-methylcyclopropene (1-MCP), edible coatings and essential oils, ozone, nano-enabled packaging, and sensor-supported decision tools. The geographical perspective is global, with explicit attention to resource-constrained supply chains.

The review question is: How should postharvest processing and storage technologies be selected for horticultural produce and grains when evidence of loss control is weighed against quality, safety, energy, cost, infrastructure, and operational risk? The novelty is a decision framework that separates established principles from transferable but condition-dependent evidence and emerging applications, while comparing lower-cost and advanced systems on the same criteria.

2. Review Approach

A structured narrative search was conducted for English-language evidence published principally from January 2000 through 22 July 2026. Search groups combined *postharvest loss*, *food loss*, *shelf life*, *quality*, or *mycotoxin* with commodity terms (fruit, vegetable, grain, cereal, pulse, apple, strawberry, maize) and technology terms (drying, solar drying, water activity, hermetic, pre-cooling, cold chain, controlled atmosphere, modified atmosphere packaging, 1-MCP, chitosan, essential oil, ozone, nanomaterial, sensor, digital twin). PubMed and publisher platforms were used to identify peer-reviewed records; Crossref, DOI, PubMed, and publisher metadata were used to verify bibliographic details. Authoritative FAO, UNEP, USDA, FDA, EFSA, Codex Alimentarius, and European Union repositories were searched for indicators, commodity guidance, and regulatory or safety documents. Reference lists were searched for landmark studies.

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Eligible sources addressed edible horticultural produce or grains after harvest and reported a mechanism, operating condition, outcome, implementation factor, or regulatory requirement relevant to the review question. Preharvest-only studies, non-crop foods, non-traceable records, duplicated references, and sources whose title or content did not support the cited claim were excluded. Primary experiments were preferred for numerical treatment effects. Reviews and institutional reports were used for established principles, synthesis, and policy context. Evidence was appraised as: (i) established, when widely commercialized or supported by consistent operational evidence; (ii) transferable with conditions, when performance depends strongly on commodity and system design; or (iii) emerging, when evidence is mainly laboratory or pilot scale or regulatory uncertainty remains. Because treatment conditions and end points were highly heterogeneous, no pooled effect or universal shelf-life multiplier was calculated.

3. Assessment of Losses

3.1 Horticultural Produce

Field heat is the sensible heat present in a commodity at harvest. It is distinct from heat gained later through solar exposure, warm loading areas, vehicle walls, respiration, or refrigeration failure. Delayed shade and cooling increase respiration and water loss; rough harvest and repeated transfers create bruises, abrasions, and compression damage. Contaminated wash water can spread microorganisms across a lot. In storage and distribution, temperature excursions, poor airflow, over-stacking, incompatible mixed loads, and condensation may become more important than the nominal set point.

Respiration and ethylene responses differ markedly among commodities and cultivars. Low temperature usually slows deterioration, but the safe temperature cannot be expressed as a generic 0-10 °C range. Temperate fruit may tolerate temperatures near 0 °C, whereas banana, mango, papaya, cucumber, eggplant, and some tomato maturity stages can develop chilling injury at low but non-freezing temperatures. The USDA commercial-storage handbook therefore specifies commodity-dependent temperature, relative humidity, expected storage duration, and physiological hazards (Gross et al., 2016). A measurement plan should record pulp or product temperature rather than air temperature alone, time to the target temperature, relative humidity, weight loss, decay, firmness or texture, color, flavor or volatile changes, and market rejection.

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3.2 Grains and Pulses

For grains, the principal control variables are initial moisture content, water activity (a_v), temperature, oxygen transfer, insect pressure, sanitation, and the water-vapor barrier of the store. Moisture content expresses water relative to product mass, whereas a_v indicates the thermodynamic availability of water and is related to equilibrium relative humidity. The relationship is product- and temperature-specific through the sorption isotherm. Thus, a single moisture content below 10-12% or an a_v below 0.3 cannot "ensure stability" for all grains, seeds, storage durations, or quality end points. Regulatory or procurement limits for a commodity are not interchangeable with a mechanistic a_v threshold (FDA, 2014).

Dry storage can prevent or slow further fungal growth and mycotoxin formation; it does not remove aflatoxin or other toxins already present. Sampling error is also important because mycotoxins can be highly heterogeneous within a lot. Appropriate outcomes include dry-matter loss, insect count, damaged kernels, germination, mold incidence, toxin concentration, price discount, and rejection; not simply visible weight loss.

3.3 A Minimum Reporting Set

Claims about effectiveness should identify the commodity and cultivar, harvest maturity and initial quality, intervention and dose, comparator, package or storage geometry, product load, temperature and relative humidity, O_2/CO_2 conditions where relevant, duration, replication, and pre-defined safety and quality end points. For field adoption, the unit of analysis should include rejected loads, downtime, maintenance, consumables, labor, energy and water use, and net value recovered. This reporting set makes biological efficacy comparable to operational performance.

4. Technology Evidence and Boundary Conditions

4.1 Drying: Control Water, Heat, Contamination, and Rewetting

Drying reduces water availability and mass for transport, but it can also cause case hardening, color change, flavor loss, vitamin degradation, lipid oxidation, and poor rehydration. Open sun drying is inexpensive and accessible but exposes food to dust, animals, insects, rainfall, uneven heating, and nighttime moisture uptake. Enclosed solar dryers improve hygiene and heat capture; their output still varies with solar radiation, load depth, airflow, collector area, and weather. Hot-air dryers provide greater control but require reliable energy. Heat-pump, infrared, microwave,

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radio-frequency, freeze, and hybrid drying can improve rate or selected quality attributes, but capital, maintenance, throughput, and non-uniform heating become decisive (Ratti, 2001; Onwude et al., 2016; Devan et al., 2020; Kong et al., 2024).

Drying should therefore be designed backwards from a product-specific safe-storage target. Moisture content and a_v should be measured after temperature equilibration, and the package must limit water-vapor transfer during the intended climate and storage time. A fast-drying rate is not automatically optimal: surface sealing can trap internal moisture, while excessive temperature may damage seed viability or heat-sensitive nutrients. Model-based drying curves are useful only after validation at the relevant bed depth and airflow (Onwude et al., 2016).

Direct-fire and smoke drying require an additional chemical-hazard assessment. Incomplete combustion and direct contact with smoke can deposit polycyclic aromatic hydrocarbons (PAHs). Codex recommends controlling fuel type and moisture, combustion conditions, distance from the heat source, smoke contact, fat dripping, and equipment cleanliness (Codex Alimentarius Commission, 2009). Applicable contaminant limits must be verified in the destination market; for example, European Union limits are consolidated in Regulation (EU) 2023/915 (European Commission, 2023). Smoke should not be treated as a free preservative benefit without measuring PAHs and sensory acceptability.

4.2 Ambient, Evaporative, and Hermetic Storage

Shade, reflective roofs, ventilated stacks, raised pallets, clean containers, and first-in-first-out rotation are low-cost controls. Evaporative cooling can lower temperature when the air is dry enough, but cooling potential diminishes as ambient humidity rises. It consumes water, raises local relative humidity, and does not provide a fixed product temperature. It is most suitable for commodities that benefit from high relative humidity and tolerate surface moisture; sanitation and drainage remain necessary.

Hermetic bags or silos restrict gas exchange. They do not instantly eliminate oxygen. O_2 declines and CO_2 rises progressively through respiration by insects, grain, and microorganisms; the trajectory depends on seal integrity, liner permeability, infestation, grain moisture, temperature, fill ratio, and duration. In an eight-month maize study, PICS bags buffered internal humidity and limited insect damage, but oxygen patterns differed between infested and non-infested bags

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(Williams et al., 2017). Opening a hermetic bag renews oxygen and moisture exchange; repeated opening has been associated with fungal growth and aflatoxin risk under unfavorable grain conditions (Tubbs et al., 2016).

Hermetic storage is therefore an insect-management and moisture-buffering tool, not a substitute for cleaning and drying. Grain must enter at a locally validated safe moisture content, liners must be inspected for punctures, and repeated retail withdrawal should use smaller units or controlled decanting. Economic value depends on bag life, counterfeit avoidance, training, harvest-time credit, and the ability to sell when prices improve. Cross-country analysis indicates that adoption and greenhouse-gas implications vary with baseline loss, reuse, and market conditions (Dijkink et al., 2022).

4.3 Pre-cooling and the Cold Chain

For most fresh produce, rapid removal of field heat followed by stable temperature management has the widest technical foundation. Room cooling is simple but often slow. Forced-air cooling draws cold air through packages and requires aligned vents, controlled pressure, and loading patterns that prevent short-circuiting. Hydro-cooling can be fast for water-tolerant commodities, but water sanitation, infiltration, disposal, and package wet strength must be managed. Vacuum cooling is especially effective for leafy products with high surface area, although evaporative mass loss and high equipment cost require water make-up and adequate throughput. Icing is limited to commodities and packages that tolerate direct water and near-0 °C conditions (Gross et al., 2016; Duan et al., 2020; Mercier et al., 2017).

Pre-cooling method selection must consider cooling rate, cultivar, package geometry, water sensitivity, sanitation, energy and water availability, and the next distribution step. A cold room cannot correct warm centers rapidly if airflow paths are blocked. Conversely, pre-cooled produce loses the benefit if it waits on an unrefrigerated dock. Time-temperature integration is more informative than a single dispatch reading because deterioration is cumulative and spatially variable (Mercier et al., 2017). Sensors should be positioned at anticipated warm points, calibrated, and linked to corrective action.

A primary strawberry supply-chain experiment illustrates both synergy and specificity. Zhao et al. combined an insulated expanded-polystyrene package, phase-change cooling, and MAP and

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found better appearance, firmness, soluble solids, color, and respiration control than the study control under the tested simulated distribution conditions (Zhao et al., 2019). This result does not establish a universal multiplier for strawberries: package size, film, initial fruit condition, atmosphere, season, transport profile, and rejection criterion govern transferability.

4.4 Controlled and Modified Atmospheres

CA storage actively measures and controls room gases; dynamic CA adjusts the low-O_2 set point in response to fruit status. MAP modifies the package headspace through gas flushing or commodity respiration and film transfer. Vacuum packaging is a distinct process and should not be used as a synonym for gas-flush MAP. For passive MAP, the eventual atmosphere emerges from the balance among respiration rate, film O_2 and CO_2 permeability, film area and thickness, perforations, fill weight, free headspace, seal quality, and temperature. Water-vapor transfer and condensation must be considered alongside gases (Sandhya, 2010; Caleb et al., 2013).

Lower O_2 and elevated CO_2 can slow respiration, ethylene action, and some spoilage organisms, but the response is commodity-, cultivar-, maturity-, temperature-, and duration-specific. Excessive CO_2 can cause tissue injury, browning, or off-flavors. O_2 below the commodity tolerance can induce fermentative metabolism, ethanol and acetaldehyde accumulation, loss of flavor, and potential microbiological concern in minimally processed foods. The safe operating window narrows during temperature abuse because respiration can rise faster than film permeability. Reviews of apple dynamic CA emphasize the risk of low-O_2 and CO_2 injury even where firmness and scald control improve (Mditshwa et al., 2018).

Accordingly, a gas recipe cannot be transferred solely because two commodities have similar respiration rates. Validation should include continuous or repeated headspace measurement, leakage testing, sensory end points after retail simulation, and challenge or hazard assessment where reduced oxygen could favor pathogens. CA and MAP are best regarded as additions to temperature control, not replacements for refrigeration or sanitation.

4.5 4.5 1-MCP, Coatings, Essential Oils, and Ozone

1-MCP binds ethylene receptors and can delay ethylene-mediated ripening and senescence. Its effect depends on crop, cultivar, maturity, time after harvest, concentration, exposure duration, temperature, and subsequent atmosphere. Some fruit may show delayed or incomplete aroma

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development or impaired recovery of ripening. Reviews and meta-analysis confirm substantial heterogeneity among climacteric fruit and response variables (Watkins, 2006; Zhang et al., 2020). Use must follow the commodity, formulation, dose, and authorization approved in the destination jurisdiction; “1-MCP treatment” is not a single transferable process.

Chitosan and other edible coatings can reduce moisture or gas transfer and serve as carriers for antimicrobials. Performance depends on polymer molecular properties, pH, plasticizer, coating thickness, drying, adhesion, and fruit surface. Chitosan source, allergen communication, and local food-contact or additive status require attention. Essential oils can inhibit microorganisms in vitro, but release from a food matrix and the concentration required for control may produce unacceptable aroma or flavor. A recent experiment on fresh-cut ‘Braeburn’ apples used a 1.5% chitosan system containing acids and oregano or cinnamon-leaf essential oil during 9 d at 4 ± 1 °C; several quality and microbial indicators improved, while higher oil concentrations affected visual or sensory performance (Ali et al., 2025). This is promising laboratory evidence, not a universal commercial treatment. Broader chitosan evidence likewise remains commodity- and formulation-specific (Romanazzi et al., 2017).

Ozone is a strong oxidant applied in water or gas. Antimicrobial effect is governed by concentration × contact time, ozone demand of organic matter, humidity, temperature, water quality, mixing, surface accessibility, and organism. Excess exposure can bleach pigments, damage tissue, oxidize lipids or aroma compounds, and corrode equipment. Worker exposure, off-gas destruction, interlocks, leak detection, and validated monitoring are mandatory. Reviews report variable efficacy and tolerance across fresh and fresh-cut produce (Miller et al., 2013; Botondi et al., 2021). In the United States, ozone use as an antimicrobial in food is governed by 21 CFR §173.368 (FDA, 2001); other jurisdictions may differ. A universal 0.1-0.5 ppm recommendation is therefore inappropriate.

4.6 Nano-Enabled Packaging and Digital Tools

Nanoclays, metal or metal-oxide particles, and nano-structured biopolymers may alter barrier, mechanical, UV, antimicrobial, or indicator functions. However, “nano-packaging” describes many materials and exposure pathways. Evaluation must identify particle size distribution, surface chemistry, loading, matrix, intended function, migration under the worst foreseeable food/time/temperature conditions, oral hazard, environmental release, recycling compatibility,

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and end-of-life behavior. EFSA guidance requires specific assessment of small particles in regulated food and feed applications (EFSA., 2021). Migration is not merely theoretical: nanosilver was released from tested commercial food containers under experimental conditions (Echegoyen & Nerín, 2013). Environmental or sustainability superiority cannot be asserted without a comparative life-cycle assessment. Most nano-enabled antimicrobial applications should therefore be labeled emerging unless the exact material and intended use have regulatory clearance and scaled validation.

Time-temperature indicators, data loggers, radio-frequency identification, predictive shelf-life models, and digital twins can reveal weak points and support first-expired-first-out decisions. They do not cool food. Data value depends on sensor accuracy, calibration, sampling interval, placement, connectivity, model validity, data ownership, and a defined response when limits are exceeded. Distributed ledgers can preserve selected records but cannot prove that the original temperature measurement was accurate. Digital twins for fresh produce remain promising because they can estimate spatial and product-specific histories, but validation and interoperability are active challenges (Defraeye et al., 2021). Intelligent logistics evidence supports decision assistance rather than autonomous assurance (Jedermann et al., 2014)

5. Comparative Evidence and Selection Framework

Table 1 summarizes representative evidence and, importantly, the conditions that limit transfer. It is not a ranking of technologies. Table 2 compares implementation demands and readiness. In both tables, “widely adopted” means that commercial examples exist; it does not imply universal suitability or regulatory authorization.

Table 1. Representative evidence and boundary conditions for postharvest interventions

Interven tion	Commo dity and study context	Operating conditions and comparato r	Reported end points	Evidence/rea diness	Principal boundary conditions	Refere nces

DOI: https://doi.org/10.65749/pjfs.2026.30.2.0012

PICS hermetic bag	Maize; eight-month primary study	Triple-layer hermetic bags, infested/non-infested treatments; woven bags as comparators; ambient temperature varied	Internal O_2/RH, moisture, insect damage, germination	Established for insect control; transferable with training	Initial moisture, puncture/seal, infestation, temperature, bag authenticity, re-opening	(Williams et al., 2017)
Re-opening hermetic bags	Maize; experimental storage	Hermetic bags opened during storage versus sealed handling	Grain quality, fungal growth, aflatoxin	Strong warning evidence	Oxygen renewal, ambient humidity, initial contamination and moisture; toxins already present are not removed	(Tubbs et al., 2016)
Integrated cold package + MAP	Fresh strawberry; simulated supply chains	Insulated EPS package, phase-change cooling and MAP	Appearance, firmness, color, soluble solids, respiration	Pilot/transferable	Cultivar, initial quality, film and pack geometry, season, time-	(Zhao et al., 2019)

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		versus study control			temperature profile, recycling of EPS/PCM	
Pre-cooling and cold chain	Multiple horticultural commodities; technical handbook and reviews	Room, forced-air, hydro-, vacuum cooling or icing selected by commodity and package	Cooling rate, mass loss, disorders, decay, market life	Widely adopted	Chilling sensitivity, vent alignment, sanitation, water/energy, refrigerant, uninterrupted distribution	(Gross et al., 2016; Duan et al., 2020; Mercier et al., 2017)
Passive/active MAP	Fresh and fresh-cut produce; reviews	Respiring product in selected film or gas-flushed package; conventional air package	Headspace gases, respiration, texture, color, decay and microbial outcomes	Widely used but highly product-specific	Temperature abuse, permeability, fill weight, perforation, condensation, anaerobiosis and seal failure	(Sandhya, 2010; Caleb et al., 2013)
Dynamic CA	Apples; review of research and practice	Low O_2 adjusted to fruit response versus static CA	Firmness, color, scald and gas injury	Commercial for selected apples	Cultivar/maturity, sensor/control accuracy, low-O_2 and high-CO_2	(Mditshwa et al., 2018)

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		or air storage			injury, operator expertise	
1-MCP	Climacteric fruit; meta-analysis and review	Formulation- and crop-specific exposures versus untreated fruit	Firmness, color, ethylene, respiration and sensory ripening	Commercial for authorized uses	Maturity, dose, exposure, temperature, cultivar, aroma/ripening recovery, jurisdiction	(Watkins, 2006; Zhang et al., 2020)
Chitosan + essential oils	Fresh-cut 'Braeburn' apple; 9 d at 4 ± 1 °C	1.5% chitosan/acid matrix with oregano or cinnamon-leaf oils versus controls	Physicochemical, antioxidant, visual and microbial indicators	Laboratory/emerging formulation	Sensory threshold, coating uniformity, oil release, chitosan source, scale-up and authorization	(Ali et al., 2025)
Ozone	Fresh/fresh-cut produce; reviews and regulation	Aqueous or gaseous treatment; dose must be validated	Surface microorganisms, decay, color, texture and oxidation	Commercial equipment; process-specific validation	C×t, ozone demand, humidity, commodity injury, worker exposure, off-gas and corrosion	Miller et al., 2013; Botondi et al., 2021; (FDA, 2014)

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Nano-enabled food contact	Commercial nanosilver containers; migration study EFSA guidance	Food simulants under defined time/temperature conditions	Particle migration and characterization	Emerging/regulated case by case	Migration, particle identity/dose, toxicity, matrix changes, environmental fate, approval and LCA	(EFSA, 2021; Echegoyen & Nerín, 2013)

Table 2. Technology selection and implementation matrix

Technology	**Best physiological or hazard fit**	**Infrastructure / utilities**	**Operator and monitoring demand**	**Cost and scalability profile**	**Resource-constrained suitability**	**Readiness / critical failure mode**
Enclosed solar or hybrid drying	Grains, pulses, sliced produce; water-activity control	Dryer, clean air, weather protection; optional backup heat	Moisture/a_v checks, loading and endpoint control	Low-moderate capital; modular; weather affects throughput	High where solar resource and maintenance exist	Established/transferable; under-drying, rewetting or overheating
Evaporative cooling	Water-tolerant produce in hot, dry air	Clean water, shade,	Wet-bulb potential,	Low capital; climate-limited	Moderate-high in arid settings	Established niche; high humidity removes

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		drainage, airflow	hygiene, daily water management			cooling capacity
Hermetic bags/silos	Dry grains/pulses; insect exclusion and modified atmosphere	Validated container and dry grain; little power	Moisture check, puncture inspection, correct sealing	Low unit capital; scalable; recurring bags/repairs	High	Widely adopted; wet grain, counterfeit/failed liner, frequent opening
Conventional cold chain	Most fresh produce at commodity-specific temperature	Pre-cooler, insulated store/vehicle, reliable power and refrigerant service	Continuous time-temperature control, airflow and calibration	High capital/operating cost; strong scale economies	Moderate where hubs, finance and service exist	Widely adopted; breaks in chain, poor loading or wrong temperature
CA storage	Long-term high-value fruit/vegetables	Gas-tight rooms, analyzers, control and backup	High skill; continuous gas and safety monitoring	High capital; requires throughput	Low for individual smallholders; possible	Commercial; leakage, gas injury, unsafe entry

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					cooperatives	
MAP	Packaged fresh/fresh-cut produce	Validated films, sealing, gas testing; often refrigeration	Medium-high design/ QC demand	Moderate; scalable at packhouse	Moderate with reliable film and cold chain	Commercial; temperature-driven anaerobiosis/condensation
1-MCP	Selected ethylene-responsive, authorized crops	Sealed treatment space/formulation; cold chain often follows	Dose, maturity, exposure and authorization control	Moderate; service models can scale	Moderate for aggregated lots	Commercial for specified uses; poor ripening/aroma or non-compliance
Edible coating/essential oil	Water-loss or surface-decay control in selected produce	Food-grade formulation, application and drying	Composition, viscosity, thickness, sensory and microbiology QC	Low-moderate equipment; formulation costs	Potentially moderate	Pilot-to-commercial depending formulation; uneven coat/off-flavor

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Ozone	Surface or water sanitation adjunct	Generator, monitor, interlocks, ventilation /off-gas	High safety and process-validati on demand	Moderate-high; no stored chemical but maintenance required	Low-modera te	Commercial equipment; worker exposure or commodity oxidation
Nano-enabled packagin g	Barrier/activ e/indicator functions for specific packs	Specialize d material supply and food-contact validation	Migrati on, specific ations, traceabi lity and end-of-life assessm ent	High development/ regulatory cost	Current ly low	Emerging; migration/toxi cology or recycling failure
Sensors/ digital twins	Detect thermal history and support logistics decisions	Calibrated sensors, connectivi ty, software and response system	Data governa nce, model validati on, correcti ve action	Modular sensors to high-cost integration	Modera te if decisio ns are actiona ble	Pilot-to-commercial; uncalibrated data or alerts without response

Selection should start with the dominant mechanism of loss, not a preferred device. For a dry grain lot with insects, hermetic containment after validated drying may outperform refrigeration. For a highly respiring berry, shade, rapid pre-cooling, suitable packaging, and stable distribution temperature are the foundation; adding MAP without temperature control can increase anaerobic

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risk. For a chilling-sensitive fruit, a lower set point can be worse than a slightly warmer, stable temperature. The following sequence is recommended:

1. Define commodity, cultivar, maturity, lot condition, hazard, and target market;
2. Locate the principal loss point using measured mass, grade, safety, and temperature/moisture data;
3. Specify the required storage or distribution time and acceptance end points;
4. Screen technologies for physiological compatibility and food-safety or worker-safety constraints;
5. Assess electricity, fuel, water, packaging, sanitation, maintenance, spare parts, skill, finance, and throughput;
6. Pilot against the current practice across realistic seasonal extremes; and
7. Scale only when value recovered exceeds total life-cycle cost and performance is monitored.

6. Quality, Nutrition, and Safety Trade-offs

"Quality retention" should not be represented by appearance alone. External color or firmness may remain acceptable while aroma, sweetness-acid balance, texture, vitamins, phenolics, or microbiological safety deteriorate. Conversely, processing may reduce a heat-sensitive vitamin while improving microbiological stability and year-round nutrient availability. Quality is commodity- and market-specific and includes sensory, nutritional, technological, convenience, and safety attributes (Kyriacou & Rouphael, 2018).

Cold storage reduces many reaction rates but can cause chilling injury and may alter volatile production. CA, MAP, and 1-MCP can retain firmness yet suppress characteristic aroma or delay ripening. Drying concentrates solids per unit mass but exposes heat- and oxygen-sensitive compounds; pretreatments may reduce browning yet create effluent or additive-labeling issues. Coatings can reduce water loss but create gloss, tack, altered gas transfer, or off-flavor. Ozone can reduce surface microorganisms without reaching protected sites, and excessive oxidation can damage tissue. These are reasons to use multi-endpoint studies and a retail-simulation period after storage.

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Food safety is not guaranteed by visual acceptability. Reduced-oxygen packaging can suppress aerobic spoilage cues while allowing tolerant hazards if temperature, pH, and product ecology are unfavorable. Hermetic storage controls insects but cannot detoxify contaminated grain. Re-circulated hydro-cooling water or wash water can spread contamination if disinfectant concentration, organic load, contact time, and replenishment are not controlled. Every technology should therefore sit within good hygienic practice, traceability, validated critical limits, and destination-market regulation.

7. Sustainability, Economics, and Adoption

Loss reduction is not automatically environmentally beneficial. The avoided product footprint should be compared with the intervention's capital equipment, electricity or fuel, refrigerant leakage, water, consumables, packaging, transport changes, and end of life. Refrigeration can prevent high-value perishable loss but also increases energy demand and refrigerant risk. Sustainable cold-chain planning combines right-sized equipment, efficient insulation and airflow, low-global-warming-potential refrigerants, leak control, renewable energy where reliable, heat recovery where useful, and high utilization (FAO & UNEP, 2022; James & James, 2010). Solar power can improve access but requires storage, backup, or operational scheduling to manage variability.

Techno-economic assessment should report capital expenditure, financing, operating energy and water, maintenance, replacement parts, consumables, labor, training, throughput, downtime, product value recovered, and sensitivity to seasonal utilization. A short laboratory shelf-life gain is not a payback calculation. For hermetic bags, reusable life, price seasonality, credit needs, and counterfeit risk may dominate. For CA rooms, packhouse scale, gas-tightness, backup power, and occupancy determine economics. For coatings or ozone, formulation or equipment service and regulatory verification may exceed the cost of the active ingredient.

Adoption is also institutional. Cooperative pre-cooling or drying hubs can spread capital across producers, but governance, scheduling, grading rules, and benefit sharing must be credible. Training should account for literacy and language, and technology design should consider who performs sorting, drying, loading, record keeping, and market sales. Labor displacement, worker exposure, gendered access to finance, and maintenance capability are part of sustainability, not

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external details. Repairability, local spare parts, and service response can be more important than peak efficiency.

Life-cycle assessment (LCA) and techno-economic analysis (TEA) are still uncommon in efficacy studies. Until comparative LCA/TEA data exist, claims such as “eco-friendly,” “low cost,” or “sustainable” should be identified as hypotheses or context-specific inferences. The appropriate comparison is the current local system, including its losses—not an idealized alternative.

8. Research Priorities

Five gaps constrain stronger recommendations. First, studies should adopt the minimum reporting set in Section 3.3 and define shelf-life failure before analysis. Second, independent multi-season and multi-location validation is needed for coatings, active films, ozone, and nano-enabled materials; laboratory pathogen inhibition does not establish commercial effectiveness. Third, postharvest trials should integrate microbiological safety, sensory acceptance, nutrition, and market grade rather than a single instrumental measure. Fourth, full-chain pilots should report temperature or moisture histories, equipment reliability, maintenance, and lot-level economic outcomes. Fifth, LCA and TEA should be paired with efficacy trials, including packaging disposal, refrigerant leakage, water treatment, and rebound effects.

For resource-constrained supply chains, research should compare modular and shared-service models: community drying with verified endpoints, aggregation-based pre-cooling, pay-per-use cold rooms, smaller hermetic units for partial withdrawal, and sensor systems whose alerts trigger feasible action. Readiness labels should distinguish laboratory proof of concept, pilot validation, initial commercial use, and widespread adoption. This prevents a novel material from being compared as if it had the same evidence and service ecosystem as refrigeration or hermetic storage.

9. Conclusion

Postharvest loss reduction is a system-design problem. The evidence does not support a universal 30-50% loss estimate, a generic 0-10 °C storage recommendation, fixed CA/MAP gas ranges, a single safe moisture or a_w threshold, or a two- to four-fold shelf-life extension across

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commodities. Each claim must be bounded by commodity, treatment, comparator, environment, duration, and endpoint.

For grains and pulses, validated drying, moisture-barrier packaging, sanitation, and hermetic storage provide accessible controls, but hermetic systems depend on dry grain, intact seals, and limited re-opening and do not remove existing mycotoxins. For fresh produce, shade, gentle handling, rapid commodity-compatible pre-cooling, and an unbroken cold chain remain the foundation. CA, MAP, 1-MCP, coatings, and ozone can add value when physiology, safety, sensory quality, authorization, and process control are validated. Nano-enabled packaging and digital twins merit targeted development, but migration, environmental fate, model validation, and regulatory readiness preclude broad claims.

The preferred intervention is therefore the simplest validated combination that controls the dominant loss mechanism, preserves safety and market quality, and can be financed, operated, maintained, and monitored in the intended chain. Comparative field evidence, LCA, TEA, and transparent readiness reporting are now more valuable than additional unbounded shelf-life claims.

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References

Food and Agriculture Organization of the United Nations. (2026). *SDG indicator 12.3.1: Global food losses*. FAO Sustainable Development Goals Data Portal. https://www.fao.org/sustainable-development-goals-data-portal/data/indicators/1231-global-food-losses/en.

United Nations Environment Programme. (2024). *Food waste index report 2024: Think eat save—Tracking progress to halve global food waste*. https://www.unep.org/resources/report/food-waste-index-report-2024.

Food and Agriculture Organization of the United Nations. (2019). *The state of food and agriculture 2019: Moving forward on food loss and waste reduction*. https://doi.org/10.4060/ca6030en.

Affognon, H., Mutungi, C., Sanginga, P., & Borgemeister, C. (2015). Unpacking postharvest losses in sub-Saharan Africa: A meta-analysis. *World Development, 66*, 49-68. https://doi.org/10.1016/j.worlddev.2014.08.002.

Gross, K. C., Wang, C. Y., & Saltveit, M. (Eds.). (2016). *The commercial storage of fruits, vegetables, and florist and nursery stocks* (Agriculture Handbook No. 66). U.S. Department of Agriculture, Agricultural Research Service. https://www.ars.usda.gov/ARSUserFiles/oc/np/TheCommercialStorageofFruitsVegetablesandFloristandNurseryStocks.pdf.

Duan, Y., Wang, G.-B., Fawole, O. A., Verboven, P., Zhang, X.-R., Wu, D., Opara, U. L., Nicolai, B., & Chen, K. (2020). Postharvest precooling of fruit and vegetables: A review. *Trends in Food Science & Technology, 100*, 278-291. https://doi.org/10.1016/j.tifs.2020.04.027.

Mercier, S., Villeneuve, S., Mondor, M., & Uysal, I. (2017). Time–temperature management along the food cold chain: A review of recent developments. *Comprehensive Reviews in Food Science and Food Safety, 16*(4), 647-667. https://doi.org/10.1111/1541-4337.12269.

Zhao, X., Xia, M., Wei, X., Xu, C., Luo, Z., & Mao, L. (2019). Consolidated cold and modified atmosphere package system for fresh strawberry supply chains. *LWT, 109*, 207-215. https://doi.org/10.1016/j.lwt.2019.04.032.

DOI: https://doi.org/10.65749/pjfs.2026.30.2.0012

Ratti, C. (2001). Hot air and freeze-drying of high-value foods: A review. *Journal of Food Engineering, 49*(4), 311-319. https://doi.org/10.1016/S0260-8774(00)00228-4.

Onwude, D. I., Hashim, N., Janius, R. B., Nawi, N. M., & Abdan, K. (2016). Modeling the thin-layer drying of fruits and vegetables: A review. *Comprehensive Reviews in Food Science and Food Safety, 15*(3), 599-618. https://doi.org/10.1111/1541-4337.12196.

Devan, P. K., Bibin, C., Shabrin, I. A., Gokulnath, R., & Karthick, D. (2020). Solar drying of fruits—A comprehensive review. *Materials Today: Proceedings, 33*, 253-260. https://doi.org/10.1016/j.matpr.2020.04.041.

Kong, D., Wang, Y., Li, M., & Liu, Y. (2024). A comprehensive review of hybrid solar dryers integrated with auxiliary energy and units for agricultural products. *Energy, 293*, 130640. https://doi.org/10.1016/j.energy.2024.130640.

U.S. Food and Drug Administration. (2014). *Water activity (a_w) in foods* (Inspection Technical Guide No. 39). https://www.fda.gov/inspections-compliance-enforcement-and-criminal-investigations/inspection-technical-guides/water-activity-aw-foods.

Codex Alimentarius Commission. (2009). *Code of practice for the reduction of contamination of food with polycyclic aromatic hydrocarbons (PAH) from smoking and direct drying processes* (CXC 68-2009).

European Commission. (2023). *Commission Regulation (EU) 2023/915 of 25 April 2023 on maximum levels for certain contaminants in food*. *Official Journal of the European Union, L119*, 103-157.

Williams, S. B., Murdock, L. L., & Baributsa, D. (2017). Storage of maize in Purdue Improved Crop Storage (PICS) bags. *PLoS ONE, 12*(1), e0168624. https://doi.org/10.1371/journal.pone.0168624.

Tubbs, T., Baributsa, D., & Woloshuk, C. (2016). Impact of opening hermetic storage bags on grain quality, fungal growth and aflatoxin accumulation. *Journal of Stored Products Research, 69*, 276-281. https://doi.org/10.1016/j.jspr.2016.10.003.

Dijkink, B., Speranza, C. I., & Baributsa, D. (2022). Hermetic bags for the storage of maize: Perspectives on economics, food security and greenhouse gas emissions in different sub-Saharan

DOI: https://doi.org/10.65749/pjfs.2026.30.2.0012

African countries. *Frontiers in Sustainable Food Systems, 6*, 767089. https://doi.org/10.3389/fsufs.2022.767089.

Sandhya. (2010). Modified atmosphere packaging of fresh produce: Current status and future needs. *LWT – Food Science and Technology, 43*(3), 381-392. https://doi.org/10.1016/j.lwt.2009.05.018.

Caleb, O. J., Mahajan, P. V., Al-Said, F. A. J., & Opara, U. L. (2013). Modified atmosphere packaging technology of fresh and fresh-cut produce and the microbial consequences—A review. *Food and Bioprocess Technology, 6*(2), 303-329. https://doi.org/10.1007/s11947-012-0932-4.

Mditshwa, A., Fawole, O. A., & Opara, U. L. (2018). Recent developments on dynamic controlled atmosphere storage of apples—A review. *Food Packaging and Shelf Life, 16*, 59-68. https://doi.org/10.1016/j.fpsl.2018.01.011.

Watkins, C. B. (2006). The use of 1-methylcyclopropene (1-MCP) on fruits and vegetables. *Biotechnology Advances, 24*(4), 389-409. https://doi.org/10.1016/j.biotechadv.2006.01.005.

Zhang, J., Ma, Y., Dong, C., Terry, L. A., Watkins, C. B., Yu, Z., & Cheng, Z.-M. (2020). Meta-analysis of the effects of 1-methylcyclopropene (1-MCP) treatment on climacteric fruit ripening. *Horticulture Research, 7*, 208. https://doi.org/10.1038/s41438-020-00405-x.

Romanazzi, G., Feliziani, E., Baños, S. B., & Sivakumar, D. (2017). Shelf-life extension of fresh fruit and vegetables by chitosan treatment. *Critical Reviews in Food Science and Nutrition, 57*(3), 579-601. https://doi.org/10.1080/10408398.2014.900474.

Ali, N., Dina, E., & Tas, A. A. (2025). Bioactive edible coatings for fresh-cut apples: A study on chitosan-based coatings infused with essential oils. *Foods, 14*(13), 2362. https://doi.org/10.3390/foods14132362.

Miller, F. A., Silva, C. L. M., & Brandão, T. R. S. (2013). A review on ozone-based treatments for fruit and vegetables preservation. *Food Engineering Reviews, 5*(2), 77-106. https://doi.org/10.1007/s12393-013-9064-5.

DOI: https://doi.org/10.65749/pjfs.2026.30.2.0012

Botondi, R., Barone, M., & Grasso, C. (2021). A review into the effectiveness of ozone technology for improving the safety and preserving the quality of fresh-cut fruits and vegetables. *Foods, 10*(4), 748. https://doi.org/10.3390/foods10040748.

U.S. Food and Drug Administration (FDA). (2001). *Ozone* (21 CFR §173.368). *Code of Federal Regulations, Title 21*.

EFSA Scientific Committee, S., Bampidis, V., Benford, D., et al. (2021). Guidance on technical requirements for regulated food and feed product applications to establish the presence of small particles including nanoparticles. *EFSA Journal, 19*(8), 6769. https://doi.org/10.2903/j.efsa.2021.6769.

Echegoyen, Y., & Nerín, C. (2013). Nanoparticle release from nano-silver antimicrobial food containers. *Food and Chemical Toxicology, 62*, 16-22. https://doi.org/10.1016/j.fct.2013.08.014.

Defraeye, T., Shrivastava, C., Berry, T., Verboven, P., Onwude, D., Schudel, S., Bühlmann, A., Cronje, P., & Rossi, R. M. (2021). Digital twins are coming: Will we need them in supply chains of fresh horticultural produce? *Trends in Food Science & Technology, 109*, 245-258. https://doi.org/10.1016/j.tifs.2021.01.025.

Jedermann, R., Nicometo, M., Uysal, I., & Lang, W. (2014). Reducing food losses by intelligent food logistics. *Philosophical Transactions of the Royal Society A, 372*(2017), 20130302. https://doi.org/10.1098/rsta.2013.0302.

Food and Agriculture Organization of the United Nations (FAO), & United Nations Environment Programme (UNEP). (2022). *Sustainable food cold chains: Opportunities, challenges and the way forward*. https://doi.org/10.4060/cc0658en.

Kyriacou, M. C., & Rouphael, Y. (2018). Towards a new definition of quality for fresh fruits and vegetables. *Scientia Horticulturae, 234*, 463-469. https://doi.org/10.1016/j.scienta.2017.09.046.

James, S. J., & James, C. (2010). The food cold-chain and climate change. *Food Research International, 43*(7), 1944-1956. https://doi.org/10.1016/j.foodres.2010.02.001.