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Sustainable postharvest management of fruits: Bridging biology, technology and policy



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Postharvest loss remains a major barrier to agricultural productivity, yet proven technologies and interventions exist to reduce it. Globally, an estimated 14% of food is lost between harvest and retail (FAO, 2019), while a further 19% of the food available to consumers is wasted in retail, food service, and households (UNEP, 2024). Fruits and vegetables are among the most perishable agricultural commodities, and their high-water content, fragile tissues, and vulnerability to mechanical injury and decay lead to value-chain losses of 20% - 50%, depending on the crop and region (Khan *et al*., 2024). Where fruit is lost depends on where it is grown. In developing regions, losses occur early, on farms and during handling, because cold storage facility is scarce and produce passes through thousands of unconnected smallholders. In developed economies, losses occur later, at retail and household levels, driven by overproduction, strict cosmetic standards and consumer behavior (Khan *et al*., 2024). Globally, these losses cost hundreds of billions of dollars annually. Due to this, growers earn less, consumers pay more, and the land, water and energy used to produce the fruit gets wasted.

Although logistics plays pivotal role in post-harvest loss reduction, however, it explains only part of the problem. Understanding quick fruit deterioration needs looking at biology. Physiological and biochemical processes going on within fruit are important in fruit spoilage. Senescence is not a simple decay, but a firmly regulated process in which ethylene plays a central role. In climacteric fruits, ethylene biosynthesis and signalling trigger a burst of respiration that drives ripening, while non-climacteric species follow quieter, ethylene-independent cues feeding into much the same genetic machinery (Tipu and Sherif, 2024). As senescence proceeds, reactive oxygen species accumulate faster than the fruit's antioxidant enzymes can neutralise them, causing lipid peroxidation and membrane damage. Simultaneously, enzymes such as polygalacturonase and cellulase break down the pectin and hemicellulose that give tissue its structure, explaining why ripe fruit softens. Chlorophyll degrades, other pigments accumulate, water is lost through transpiration, and starch converts into sugar, rewriting colour, texture, and flavour within days. Ethylene and abscisic acid pathways, alongside carbohydrate and ROS metabolism, remain the principal molecular drivers of this decline across both fruit classes (Storch *et al*., 2025). Every serious postharvest intervention such as cold chain, packaging, coating, or biocontrol agent, works by interrupting one of these triggers rather than masking its effects.

Conventional refrigeration is the obvious starting point, but it is energy intensive, still largely dependent on hydrofluorocarbons, and out of reach for smallholders without reliable grid access. Low carbon alternatives are beginning to close this gap. Solar photovoltaic cold storage, paired with cold thermal energy storage using ice, chilled water, or phase change materials, keeps cooling running through cloudy days and after dark, making it more dependable in weak-grid settings and considerably lower carbon than diesel backed refrigeration over its lifetime (Mehtab *et al*., 2026). Passive evaporative systems achieve much the same result with no electricity at all such as charcoal coolers, clay pot devices, and cooling blankets exploit evaporative cooling to lower produce temperature by 3–10°C and raise relative humidity to 70–100%, buying several extra days of shelf life (Defraeye *et al*., 2023). Field trials in tropical value chains report postharvest loss reduction of up to 45% from these passive systems, rivalling far costlier mechanical options. Where cold chains manage the environment fruit sits in, modified and controlled atmosphere packaging (MAP/CAP) manages the microclimate around each piece, adjusting oxygen, carbon dioxide, and nitrogen levels to slow respiration, delay ripening, and hold microbial growth in check. It is among the most commercially proven postharvest tools, yet its dependence on petroleum based films has pushed research toward starch, chitosan, and cellulose based alternatives that now match synthetic films for barrier performance while breaking down naturally once discarded.

Edible coatings extend this idea further, forming a semipermeable layer directly on the fruit's surface that regulates respiration, water loss, and gas exchange while carrying active compounds where they are needed. Chitosan, alginate, and gum arabic dominate this space for their antimicrobial properties, film forming stability, and compatibility with plant derived actives such as essential oils, which additionally slowdown enzymatic browning and limit lipid peroxidation restraining senescence on several fronts at once. Because these materials are renewable, non-toxic and compostable, they align with both circular economy goals and clean label consumer preferences.

Non-thermal physical treatments offer a chemical free complement to these methods without sacrificing sensory quality or nutrition. Cold plasma, produced by ionising gas at room temperature, generates reactive oxygen and nitrogen species, UV photons, and charged particles that eliminate surface pathogens while pushing the fruit's own metabolism. Reported microbial log reductions of 2.0–5.0 across fruit types match or exceed conventional sanitisers without heat damage (Shill

and Sit, 2025), while also stimulating antioxidant enzyme activity that helps preserve phenolic and flavonoid content. Pulsed light, UV-C, ozone, and electrolysed water work through related mechanisms, suppressing spoilage organisms with little effect on firmness, colour, or vitamin content, a natural complement to cold chains and packaging rather than a replacement.

A different, biological line of defence targets pathogens directly. *Botrytis cinerea, Penicillium*, and *Alternaria* species collectively account for 35–50% of postharvest fruit losses each year, historically controlled with synthetic fungicides whose long-term overuse has bred resistance and raised consumer health concerns (Godana *et al*., 2026). Biocontrol agents such as antagonistic yeasts, bacteria, and filamentous fungi, offer a genuinely sustainable alternative, competing for nutrients and space, producing antifungal metabolites, forming protective biofilms, and activating the fruit's own defences. Research is moving past single-strain products toward compatible microbial consortia, including yeast-bacteria combinations from naturally fermented foods, which cast a wider antagonistic net and hold up better under commercial variability than any single organism. None of these interventions work well unless growers know precisely when and where to apply them, and digital, AI-enabled tools are turning postharvest management from reactive inspection into predictive, data-driven decision-making. In developing regions, where losses from rotting, mechanical damage, and inconsistent grading can reach 40–80% in the worst cases, AI-augmented sensing is beginning to address these inefficiencies directly (El-Beltagi *et al.,* 2025). Non-destructive imaging i.e., RGB, hyperspectral, near-infrared and X-ray methods, combined with deep learning models such as convolutional neural networks can now assess soluble solids, firmness, internal defects, and ripeness stage quickly and objectively, replacing subjective sampling. Connecting these systems to Internet-of-Things sensor networks enables continuous, real-time monitoring across the supply chain, catching problems before quality slips (El-Beltagi *et al*., 2025). Paired with robotic sorting and grading, this is already improving throughput, consistency, and traceability from farm to retail shelf.

Even with better cooling, packaging, sanitation, biocontrol and monitoring in place, some fruit will always be rejected and this is where circular-economy thinking earns its keep, treating discarded pomace, peels, and cosmetically rejected fruit as an underused source of valuable biomolecules rather than waste. Of the roughly 1.3 billion tonnes of edible food lost or wasted globally each year, much of this material still contains vitamins, fibre, polyphenols and prebiotic compounds, sometimes at higher concentrations than in fruit that reached market (Worku *et al*., 2026). Green extraction methods such as ultrasound-assisted extraction, supercritical fluid extraction and deep eutectic solvent systems recover these bioactives efficiently and with a light environmental footprint, feeding into nutraceuticals, functional foods, and biodegradable packaging while opening new revenue streams for growers. Integrated biorefineries take this further by turning fruit waste into energy, biofertiliser and microbial growth media. This eases pressure on food supplies, cuts landfill methane, and supports SDG 12's goal of halving food waste.

Technology alone, though, will not end postharvest loss. In smallholder economies, 15-50% loss persist not because solutions are missing, but due to financial limitations, poor coordination of institutions, implementation is irregular, and extension services are under considerable pressure due to resource constraints. Closing the gap requires farmer training, locally adapted technologies, wider credit access, stronger policies, and integration of postharvest practices into climate-smart value chains from the outset. Postharvest management is a core component of food security and climate policy, reducing losses, improving efficiency, and strengthening resilience while advancing SDG 2 (Zero Hunger) and SDG 12 (Responsible Consumption and Production).

From senescence physiology to low-carbon cooling, sustainable packaging, non-thermal decontamination, microbiome-based biocontrol, AI monitoring, and waste recovery, these approaches demonstrate that no single technology can address postharvest challenges in isolation. Their strength lies in integration: a cold chain depends on packaging that protects fruit beyond storage; AI monitoring only matters when it leads to real corrective action; and recovering bioactives from waste cannot replace the imperative of preventing waste in the first place. Future research and investment must shift from testing technologies in isolation to designing integrated systems that combine physiological insight, low-carbon engineering, biological control, digital sensing, and waste valorisation. Priority should focus on smallholder and off-grid producers; those most vulnerable to losses and least able to invest and on interdisciplinary collaboration across plant physiology, materials science, microbiology and data science. Financing mechanisms that reduce adoption risks should support these efforts. Integration is essential not only to lower the economic burden of postharvest loss, but also to advance global commitments on food security and climate resilience under SDG 2 and SDG 12.

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