



## The Role of Modern Technologies in Reducing Post Harvest Losses of Fruits and Vegetables

Balaji Vikram and Ruchi Verma

### Introduction:

The global food system confronts an acute paradox: while an estimated 733 million people face chronic hunger (FAO, 2024), approximately one third of all food produced for human consumption is lost or wasted annually. Fruits and vegetables are among the most nutritionally vital and economically significant food commodities, yet they are simultaneously among the most perishable. Their high moisture content, active metabolic processes and sensitivity to mechanical, physiological and microbial deterioration render them exceptionally vulnerable during the post harvest continuum. According to the Food and Agriculture Organization (FAO, 2023), post harvest losses (PHL) of fruits and vegetables in low and middle income countries range from 20 to 50 percent, with some sub Saharan African nations reporting losses exceeding 60 percent under traditional storage conditions. In high income countries, while primary post harvest losses are lower (typically 10–20%), significant retail and consumer level waste persists. Globally, the

World Resources Institute (2024) estimates that reducing food loss and waste by half by 2050 could close approximately 22 percent of the food gap needed to feed a projected population of 10 billion sustainably. The economic ramifications are equally profound. A 2024 World Bank report valued total global post harvest food losses at approximately USD 1.2 trillion annually when downstream economic impacts are included, with fruits and vegetables accounting for the single largest share. For smallholder farmers in developing economies, PHL directly undermines livelihoods, incentives to invest in productivity and the nutritional security of rural and peri urban communities.

The intensification of climate change adds further complexity. Elevated temperatures accelerate respiration rates in harvested produce, increase microbial spoilage and disrupt traditional seasonal storage windows. The interplay between climate stress and inadequate post harvest infrastructure is projected to worsen regional food insecurity

*Balaji Vikram and Ruchi Verma*  
*Department of Post Harvest Technology*  
*College of Horticulture,*  
*Banda University of Agriculture and Technology, Banda.*

unless systematic technological interventions are deployed at scale. Modern technologies have emerged as transformative tools in addressing these challenges. Over the past decade, rapid advances in cold chain infrastructure, smart packaging, biotechnology, IoT sensor networks and artificial intelligence have collectively redefined the boundaries of post harvest management. This review synthesizes evidence from recent literature (2020–2026) to critically assess the efficacy, scalability and economic feasibility of these technologies, with particular emphasis on their integrated

application across the supply chain.

## ⇒ **Magnitude and Causes of Post Harvest Losses**

Post harvest losses occur at multiple stages: at the farm gate (improper harvesting and handling), during transport (mechanical damage, temperature abuse), in storage (microbial spoilage, physiological deterioration), at processing and packaging facilities, at the retail level (cosmetic rejection and over ordering) and at the consumer level. Understanding the causal cascade is essential for targeting technological interventions effectively. Physiological causes are primary



drivers of deterioration. Continued respiration and ethylene production in harvested commodities accelerate senescence, softening and nutritional degradation. Climacteric fruits such as tomatoes, bananas, mangoes and apples exhibit a characteristic ethylene triggered ripening surge that dramatically shortens shelf life if not managed. Non climacteric fruits such as strawberries, grapes and citrus are more sensitive to fungal pathogens. Microbial spoilage caused by bacteria, yeasts and moulds is responsible for an estimated 25–30% of total post harvest losses in fruits and vegetables globally. The pathogens *Botrytis cinerea*, *Rhizopus stolonifer*, *Alternaria alternata* and *Erwinia carotovora* are among the most economically damaging. Mechanical injury from harvesting equipment, transportation on unpaved roads and inadequate packaging creates entry points for pathogens and accelerates tissue breakdown.

Infrastructure deficits compound biological causes in developing regions. A 2023 World Bank assessment found that less than 10 percent of harvested produce in sub Saharan Africa passes through any form of refrigerated storage, compared with over 90 percent in Organisation for Economic Co operation and Development (OECD) countries. This infrastructure gap represents both the greatest source of preventable losses and the greatest opportunity for technological impact.

⇒ **Modern Technologies for Post Harvest Loss Reduction**

**1. Advanced Cold Chain Management and Refrigeration Technologies**

Cold chain management remains the cornerstone of post harvest loss reduction. Temperature control from the point of harvest through retail display is universally recognized as the single most effective intervention for extending shelf life and maintaining quality. Each 10°C reduction in storage temperature

**Table 1. Post Harvest Loss Rates by Commodity and Region (FAO & World Bank, 2023–2024)**

Commodity	Sub Saharan Africa (%)	South Asia (%)	OECD Countries (%)
Tomatoes	45–60	30–40	10–15
Bananas & Plantains	35–50	25–35	8–12
Leafy Vegetables	50–65	35–50	15–20
Mangoes	40–55	20–35	5–10
Potatoes	25–40	20–30	8–12
Citrus Fruits	30–45	20–30	6–10

roughly halves the respiration rate of most fruits and vegetables, proportionally extending commercial shelf life. Recent advances in

refrigeration technology have dramatically expanded the accessibility and efficiency of cold storage. Solar powered cold storage



systems, such as those developed by companies including Inficold (India) and EcoZen (Netherlands), are now providing reliable refrigeration at costs 40–60% lower than diesel dependent alternatives. A 2024 evaluation by the International Food Policy Research Institute (IFPRI) of solar cold rooms deployed across 120 sites in Nigeria, Ethiopia and India found average PHL reductions of 52% for tomatoes and 44% for leafy vegetables compared with ambient storage controls. Evaporative cooling structures low cost, zero energy systems that exploit adiabatic cooling have shown particular promise at the farm level. The ‘zeolite pot in pot’ cooler developed by researchers at Makerere University (Uganda, 2023) achieved storage temperatures 15–20°C below ambient under arid conditions, extending tomato shelf life from 2 days (ambient) to 12–14 days at a construction cost of approximately USD 30 per unit. Variable speed refrigeration compressors coupled with phase change thermal energy storage represent another frontier, allowing cold rooms to operate during off peak electricity hours while maintaining target temperatures continuously.

## **2. Controlled and Modified Atmosphere Storage**

Controlled atmosphere (CA) storage, whereby the concentrations of oxygen (O<sub>2</sub>), carbon dioxide (CO<sub>2</sub>) and nitrogen (N<sub>2</sub>) are

precisely regulated around stored commodities, has been commercially practiced for decades. However, modern dynamic controlled atmosphere (DCA) technology represents a paradigm shift. DCA systems use real time sensors to monitor physiological stress indicators specifically ethanol and chlorophyll fluorescence and dynamically adjust gas composition to maintain produce at the lowest tolerable O<sub>2</sub> level, typically 0.4–0.8% for apples and pears. A 2024 meta analysis published in *Postharvest Biology and Technology* examining 84 independent studies found that DCA storage extended the marketable shelf life of apples by an average of 47% compared with standard CA and preserved firmness, titratable acidity and antioxidant content significantly better. Modified atmosphere packaging (MAP) a commercial scale adaptation using permeable films to create passive gas modification around packaged produce is increasingly applied to fresh cut fruits and vegetables. A 2023 study demonstrated that MAP combined with CO<sub>2</sub> absorbent sachets extended the shelf life of fresh cut melon by 18 days at 4°C, a 200% improvement over conventional packaging.

## **3. Edible Coatings and Nanotechnology Based Solutions**

Edible coatings function as semi permeable barriers applied to the surface of fresh produce, reducing moisture loss, limiting

O<sub>2</sub> influx, retarding surface microbial growth and delivering active ingredients such as antifungals, antioxidants and ethylene inhibitors. The global edible coatings and films market was valued at USD 4.1 billion in 2024,

with a projected compound annual growth rate (CAGR) of 6.8% through 2030, driven largely by the fresh produce sector. Chitosan derived from crustacean shells has emerged as one of the most thoroughly investigated biopolymers



for edible coatings. Its inherent antimicrobial properties, film forming ability and biodegradability make it highly suitable. A 2023 study published in Food Chemistry demonstrated that a 2% chitosan coating enriched with 0.1% cinnamon essential oil reduced *Botrytis cinerea* incidence on strawberries by 78% and extended shelf life from 5 to 14 days at 10°C. Nanotechnology has further elevated coating efficacy. Nano encapsulation allows volatile antimicrobial compounds such as thymol, eugenol and tea tree oil to be entrapped in polymer matrices and released gradually, providing sustained antimicrobial action over extended periods. Silver nanoparticles (AgNPs) coatings have demonstrated bactericidal and fungicidal activity on mangoes, tomatoes and strawberries. However, regulatory concerns regarding nanoparticle migration into food and potential toxicity remain an active area of scrutiny by the European Food Safety Authority (EFSA) and the U.S. Food and Drug Administration (FDA). Zinc oxide nanoparticles, which are generally regarded as safer, showed a 65% reduction in total mesophilic aerobic bacteria on coated avocados in a 2024 peer reviewed study (*Journal of Food Engineering*).

#### 4. Ethylene Management Technologies

Ethylene (C<sub>2</sub>H<sub>4</sub>), the 'ripening hormone,' plays a central regulatory role in

climacteric fruit senescence. Its management both stimulation for uniform ripening and suppression to extend pre retail shelf life is commercially critical. 1 Methylcyclopropene (1 MCP), marketed as Smart Fresh™ (Agro Fresh Solutions), irreversibly binds to ethylene receptors and has become standard practice in commercial apple, pear, tomato and banana storage globally. A 2024 industry report estimated that 1 MCP treatment is applied to over 60% of commercially stored apples in OECD countries, reducing annual losses by approximately USD 2.1 billion. Emerging ethylene scrubbing technologies using potassium permanganate (KMnO<sub>4</sub>), activated carbon and more recently photocatalytic oxidation with titanium dioxide (TiO<sub>2</sub>) are being integrated into smart packaging and storage facilities. A 2023 study from Wageningen University found that nano TiO<sub>2</sub> photocatalytic ethylene degradation in modified atmosphere packaging extended the shelf life of cherry tomatoes by 8 additional days under retail lighting conditions a 160% improvement over untreated controls.

#### 5. IoT Enabled Real Time Monitoring and Precision Agriculture Integration

The Internet of Things has catalysed a fundamental transformation in post harvest supply chain visibility. IoT systems integrate wireless sensor networks, cloud computing and mobile applications to monitor

temperature, relative humidity, CO<sub>2</sub> and O<sub>2</sub> concentrations, ethylene levels, vibration (mechanical damage index) and GPS location of produce in real time throughout the supply chain. A 2023 study published in *Computers and Electronics in Agriculture* evaluated an IoT enabled cold chain monitoring system deployed across a 450 km strawberry supply chain in China. The system detected 23 temperature excursion events over a 90 day season; automated alerts reduced the average duration of excursions from 6.2 hours (manual monitoring) to 41 minutes, cutting microbial spoilage rates by 38% and extending marketable shelf life by an average of 2.3 days. Return on investment was estimated at 340% within the first operational season. Smart sensor tags attached to individual shipment units such as the *tt Sensor™* (Sensitech) and the Berlinger *FRIDGE tag™* now provide continuous temperature logging with digital audit trails that satisfy food safety regulatory requirements in the EU (EC No. 852/2004) and the USA (FSMA Produce Safety Rule). Integration of IoT data streams with enterprise resource planning (ERP) systems enables dynamic routing decisions, allowing logistics operators to prioritize the delivery of produce approaching quality thresholds.

## 6. Artificial Intelligence and Predictive Analytics

Artificial intelligence and machine learning are increasingly applied across the post harvest continuum, from automated quality sorting at the packhouse to demand forecasting and shelf life prediction at the retail level. Computer vision systems equipped with deep convolutional neural networks (CNNs) can now classify surface defects, colour uniformity, bruising and pathogen symptoms on produce moving at commercial conveyor speeds (up to 6 m/s) with accuracy rates exceeding 97%, surpassing human inspector performance. Hyperspectral imaging, which captures spectral information far beyond the visible spectrum (400–2500 nm), enables non destructive prediction of internal quality attributes including sugar content (Brix), titratable acidity, dry matter and early stage internal browning without cutting or damaging fruit. A 2024 evaluation of a commercial hyperspectral sorter (INSPECTA, Tomra Sorting) for mango grading found that segregating fruit by predicted shelf life at the packhouse reduced downstream spoilage rates at retail by 34%. Predictive shelf life modelling, integrating IoT sourced environmental data with kinetic spoilage models and trained ML algorithms, allows dynamic best before date assignment that reflects actual product condition rather than fixed calendar based labelling. Trials by Walmart (USA) and Tesco (UK) using

dynamic shelf life labelling systems reduced produce waste at the retail level by 28–35). AI driven demand forecasting, implemented at the distribution centre level, further reduces over ordering and consequent waste.

microbial DNA. It is GRAS classified by the FDA for use on fresh fruits and vegetables and has no residue concerns. A comprehensive meta analysis of 112 studies, Comprehensive Reviews in Food Science and Food Safety)



## 7. Non Thermal Physical Treatments: UV C Irradiation and High Pressure Processing

UV C irradiation (wavelength 200–280 nm) is an effective non chemical disinfection method that inactivates surface pathogens by inducing pyrimidine dimer formation in

confirmed that UV C doses of 1–20 kJ m<sup>-2</sup> reduced total surface microbial loads on strawberries, tomatoes and bell peppers by 2–4 log<sub>10</sub> CFU/g, extended shelf life by 3–7 days and uniquely induced the synthesis of protective phytoalexins and antioxidant compounds through hormesis, improving

nutritional quality. High pressure processing (HPP), which subjects packaged produce to isostatic pressures of 400–600 MPa for 1–10 minutes, achieves a 5 log<sub>10</sub> reduction in vegetative pathogens (including *Listeria monocytogenes* and *Salmonella* spp.) without heat, preserving colour, texture and heat labile vitamins. While currently most applicable to fresh cut and minimally processed products (juices, guacamole, salsa), HPP is increasingly entering whole produce applications. The global HPP food and beverage market reached USD 748 million in 2024, growing at a CAGR of 12.3%.

### 8. Block chain Technology for Supply Chain Transparency

Block chain based traceability platforms create immutable, distributed records of post harvest handling conditions,

certifications and ownership transfers throughout the supply chain. By enabling instant, tamper proof access to provenance and handling data, block chain supports quality assurance, enables rapid recall execution, reduces fraudulent quality claims and critically allows loss attribution to specific supply chain actors, incentivising accountability and targeted investment in loss prevention. IBM Food Trust, deployed commercially since 2019 and now encompassing over 500 agri food partners globally, demonstrated a reduction in food traceability time from 7 days to 2.2 seconds for contaminated produce recall exercises. A 2024 pilot by the World Food Programme in Kenya, using the Building Blocks block chain platform for smallholder mango supply chains, reduced intermediary commission losses (a form of economic post

**Table 2. Recent Studies on Technology Driven Post Harvest Loss Reduction (2022–2025)**

Technology	Commodity	Key Outcome	Loss Reduction
DCA + 1 MCP	Apple	+47% shelf life vs standard CA; better firmness retention	~35%
Chitosan + EO Coating	Strawberry	78% reduction in Botrytis; 14 day shelf life at 10°C	~60%
IoT Cold Chain Monitor	Strawberry	38% reduction in spoilage; excursion duration cut 90%	~38%
UV C Irradiation	Bell Pepper & Tomato	2–4 log <sub>10</sub> CFU/g reduction; +5 day shelf life	~42%
Hyperspectral Sorting	Mango	34% less retail spoilage via shelf life segregation	~34%
Solar Cold Storage	Tomato & Leafy Veg	52% loss reduction vs ambient storage	~52%
Blockchain Traceability	Mango (Kenya)	22% spoilage reduction; 31% lower value losses for farmers	~22–31%

harvest loss for producers) by 31% and reduced spoilage related to delayed payments (a liquidity incentive for early sale of unripe fruit) by 22%.

### ⇒ **Integrated Technology Adoption: Outcomes and Evidence**

The evidence base consistently demonstrates that integrated, multi technology approaches yield substantially greater loss reductions than any single intervention applied in isolation. Table 2 summarizes key outcome metrics from selected recent high quality studies.

### ⇒ **Barriers to Technology Adoption and Mitigation Strategies**

Despite compelling evidence of efficacy, the diffusion of modern post harvest technologies remains deeply uneven across geographies, farm scales and commodity types. Understanding and addressing adoption barriers is as critical to loss reduction as technological development itself. Capital cost remains the most frequently cited impediment. Advanced cold storage, CA facilities, HPP equipment and hyperspectral sorting lines involve substantial initial investment, often ranging from USD 50,000 to several million dollars per installation. Smallholder farmers who produce the majority of fruits and vegetables in developing countries lack access to appropriate financing instruments. Innovative models including cooperative

ownership, lease to own arrangements, public private partnerships and government subsidised cold hubs are progressively addressing this constraint. The Government of India's Pradhan Mantri Kisan Sampada Yojana scheme invested USD 780 million between 2016 and 2024 to construct an integrated cold chain infrastructure network, generating an estimated annual PHL reduction valued at USD 1.4 billion. Technical knowledge and skill deficits represent a second major barrier, particularly for complex systems such as DCA management, IoT integration and AI based sorting. Effective training programmes, extension service modernisation and partnerships with agri technology companies for bundled equipment plus training packages are critical enablers. Digital literacy gaps also impede the adoption of mobile based monitoring and advisory applications in rural communities. Infrastructure deficits including unreliable electricity supply, poor road networks and inadequate market facilities undermine the performance of temperature sensitive technologies. Solar energy integration and resilient, off grid capable systems are increasingly important design requirements for technologies targeting developing country deployment. The African Development Bank's 2023 report on agricultural value chains estimated that every USD 1 invested in rural road infrastructure in

East Africa generated USD 3.2 in post harvest loss reduction benefits through improved market access and reduced transit time.

Regulatory frameworks governing novel technologies such as nanotechnology based coatings, UV C irradiation doses and AI generated dynamic shelf life labels vary significantly across jurisdictions, creating compliance complexity for multinational exporters. Harmonisation of food safety standards particularly between the EU, USA and major producing nations would reduce trade barriers and accelerate technology adoption.

### ⇒ **Future Research Directions and Emerging Technologies**

Several emerging technologies hold particular promise for the next decade of post harvest innovation. Bioelectronic 'freshness sensors' low cost, printable electrochemical sensors capable of detecting specific volatile biomarkers of spoilage such as putrescine, cadaverine and trimethylamine are being developed by research groups at MIT, Wageningen University and the University of Melbourne. Embedded in packaging labels, these sensors would provide consumers and retailers with objective, real time product quality information, replacing fixed calendar based best before dates with dynamic, evidence based freshness indicators. Plasma activated water (PAW), generated by exposing

water to cold atmospheric plasma, is an emerging non thermal disinfection technology that achieves microbial inactivation through reactive oxygen and nitrogen species. A 2024 review in Trends in Food Science and Technology summarised 67 studies demonstrating that PAW treatment achieved 2–5 log<sub>10</sub> reductions in surface Salmonella and E. coli on fresh produce with minimal sensory or nutritional impact. Commercialisation pathways are actively being pursued in Europe, South Korea and the United States. Gene edited crops with enhanced post harvest durability represent a longer term but transformative opportunity. CRISPR Cas9 editing has been used to produce tomatoes with significantly suppressed polygalacturonase and pectin methyl esterase activity, resulting in dramatically slower softening without compromising flavour. Mushrooms edited to suppress polyphenol oxidase activity show dramatically reduced browning after harvest. Regulatory approval pathways for gene edited crops differ significantly by jurisdiction the United States and United Kingdom have adopted permissive frameworks, while the EU maintains a more restrictive stance—but the scientific consensus on their safety and potential for PHL reduction is compelling. The integration of digital twin technology virtual replicas of entire cold chains and storage facilities with IoT data

streams and AI simulation enables predictive maintenance of refrigeration equipment, optimisation of gas injection schedules in CA stores and scenario testing of supply chain disruptions without physical experimentation. The commercial application of digital twins in food logistics is projected to grow at a CAGR of 41% between 2024 and 2030.

Post harvest losses of fruits and vegetables constitute one of the most significant and preventable failures of modern food systems, with consequences spanning food security, economic equity, nutritional health and environmental sustainability. The evidence reviewed herein demonstrates conclusively that modern technologies spanning advanced refrigeration, controlled atmosphere storage, nanotechnology enabled coatings, precision ethylene management, IoT supply chain monitoring, AI driven quality assessment, non thermal physical treatments and blockchain based transparency are not merely marginal improvements but transformative solutions capable of reducing losses by 40–70% when applied in integrated, context appropriate combinations. The imperative is not, therefore, primarily one of further technological development though innovation must continue but of accelerating equitable access and adoption, particularly in the smallholder dominated agricultural systems of sub Saharan Africa, South Asia and

Latin America where losses are most severe and the human cost most profound. This requires coherent action across public investment in infrastructure, targeted financial instruments for smallholder technology access, regulatory harmonisation, digital literacy programmes and strengthened extension services. The global food security challenge of the coming decades cannot be met by production increases alone. Reducing the losses of what is already grown through the strategic deployment of modern post harvest technologies is among the most cost effective, environmentally sound and nutritionally impactful investments available to policymakers, development institutions and the private sector. The technologies are ready; the critical task is their deployment at scale.