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Digital Twin–Enabled Smart Cold Chains for Fresh Fruits

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Abstract: -

Postharvest losses in fruits exceed 30–50% in developing regions due to poor cold chain management; digital twins create virtual replicas of shipments using IoT sensors for real-time monitoring of temperature, humidity, and ethylene, enabling predictive simulations that optimize conditions, extend shelf life, and reduce spoilage by up to 43% in strawberries and citrus via AI-driven adjustments.

Keywords: Digital twin, postharvest losses, cold chain, IoT sensors, shelf-life prediction.

Introduction:

Postharvest losses in fresh fruits, often exceeding 30–50% in developing regions, arise primarily from suboptimal cold chain management involving temperature fluctuations, humidity variations, and delayed logistics (Rodolfo *et al.*, 2022). Such inconsistencies accelerate metabolic activity, moisture loss, and microbial spoilage, making quality control difficult across long distribution routes. Digital twin technology addresses these challenges by creating a virtual replica of physical fruit shipments, integrating real-time IoT sensor data on temperature, humidity, and ethylene levels to accurately mirror and predict quality degradation (Huang and Badakhshan, 2024). By enabling continuous monitoring and scenario-based simulations, this approach supports dynamic optimization of storage and transport conditions, ultimately reducing spoilage and enhancing sustainability in fruit supply chains (Zou *et al.*, 2025).

Digital Twin Architecture and Performance Benefits in Fresh Fruit Logistics

Digital twins synchronize physical fruit pallets with virtual models using IoT sensors

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and AI algorithms to monitor core metrics like firmness, color change, respiration intensity, and microbial growth in real time (Zou *et al.*, 2025). These systems continuously ingest data from embedded temperature loggers, humidity probes, ethylene sensors, and vibration trackers, allowing the virtual environment to replicate the exact physiological status of the fruit at any point in the supply chain. This high-resolution monitoring helps detect subtle stress events—such as condensation spikes or micro-cracks caused by mechanical impact—long before they become visible quality defects.

For instance, physics-based models simulate heat transfer, moisture diffusion, and respiration rates in sensitive commodities like strawberries or citrus, predicting remaining shelf life with high accuracy and alerting operators to risks such as temperature abuse during transit (Onwude *et al.*, 2022). These simulations can also evaluate how packaging type, pallet stacking pattern, and container airflow influence internal temperature gradients. In practical applications, systems trialed for orange harvests have quantified mass loss variability across packhouse-to-retail stages, enabling optimization of refrigeration setpoints, loading densities, and transport routes to cut losses by up to 43% (Onwude *et al.*, 2022).

Implementation integrates cloud computing for seamless data fusion from distributed wireless sensors, machine learning models for early decay forecasting, and automated feedback loops that dynamically adjust vehicle cooling capacity or reroute shipments to minimize quality deterioration (Huang and Badakhshan, 2024). These adaptive controls allow the system to shift from static, schedule-based cooling to demand-driven, intelligent climate management.

Case studies in strawberry cold chains demonstrate significant shelf-life extension through scenario simulations that evaluate alternative airflow velocities, humidity controls, packaging permeability, and stacking geometries. Such predictive simulations help operators identify optimal conditions before implementation, reducing trial-and-error costs and improving decision-making accuracy.

Across commercial deployments, benefits include 12–25% reductions in logistics costs, enhanced traceability for food safety audits and export certifications, and measurable reductions in CO_2 emissions due to more efficient energy use in reefer containers (Zou *et al.*, 2025) Additionally, digital twins improve transparency between growers, packers, exporters, and retailers, supporting more accurate demand forecasting, reduced overcooling, and better risk management during long-distance shipments.

Next-Generation Innovations in Digital Twin Technology for Postharvest Systems

Future advancements will integrate digital twins with non-destructive imaging technologies such as hyperspectral, X-ray, or millimeter-wave sensors for high-resolution, in-transit ripeness prediction and early detection of internal defects that are invisible to RGB cameras . These imaging-enhanced twins will allow the system to continuously assess biochemical markers, such as chlorophyll breakdown, water stress signatures, and early fungal colonization, providing more accurate forecasts of remaining shelf life.

Blockchain integration is expected to strengthen immutable provenance tracking, enabling every temperature deviation, handling event, or quality change to be securely recorded from harvest to retail. This will support export compliance, anti-fraud protection, and real-time trust verification between growers, logistics providers, and retailers.

Hybrid AI-physics models are projected to enable region-specific digital twins for major tropical fruits by incorporating localized climate data, packaging variations, and typical transport durations. These models will better predict losses in volatile, long-distance supply chains where fruits are exposed to extreme humidity and temperature fluctuations (Zou *et al.*, 2025). Such adaptive twins will also simulate how monsoon variability or heatwaves influence respiration rates and cooling efficiency.

Scalable edge computing is expected to facilitate low-cost deployments, especially in emerging markets with limited internet connectivity. By processing sensor data directly on trucks or containers, edge-enabled twins can provide instant alerts, reduce cloud costs, and support micro-cold chain networks for smallholder farmers. With broader adoption, these cost-efficient systems have the potential to reduce global fruit waste by up to half by 2030 .

Importance

Digital twins revolutionize fruit logistics by minimizing massive 30-50% postharvest losses through early detection of stress events like condensation or temperature abuse, slashing logistics costs by 12–25% via demand-driven cooling, improving food safety traceability for audits and exports, reducing CO_2 emissions through energy-efficient reefer operations, enabling precise shelf-life predictions for better demand forecasting, and fostering collaboration across growers, packers, and retailers to cut waste and boost profitability in long-distance supply chains.

Limitations

Despite benefits, digital twins face high upfront costs for IoT sensors and cloud infrastructure, require specialized technical expertise for setup and maintenance, depend on reliable high-speed connectivity that's often lacking in rural or developing regions, encounter challenges in data fusion from heterogeneous sources, raise privacy/security concerns with sensitive supply chain data, and demand standardized models for diverse fruit varieties and regional conditions to ensure scalability and accuracy.

Conclusion

Digital twin–enabled smart cold chains shift postharvest fruit management from a reactive approach to a predictive, data-driven system. By mirroring the physical state of fruit shipments in real time, digital twins help anticipate spoilage risks, maintain optimal storage conditions, and ensure more consistent quality throughout the supply chain. This results in reduced losses, better resource utilization, and higher operational efficiency.

Widespread adoption, however, will depend on overcoming practical barriers such as the cost of sensors, availability of technical expertise, and the need for reliable connectivity—especially in developing regions. Even so, evidence from early trials demonstrates substantial improvements in quality retention, traceability, and energy efficiency, highlighting the strong potential of digital twins to strengthen global food systems and support long-term sustainability.

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