



TRANSFORMING FOOD ANALYSIS AND CONTROL:

NON-DESTRUCTIVE TECHNOLOGIES AND INNOVATIONS

K. Prasad, S. Shekhar, M. K. Paswan and R. Ahuja



Advancing Food Quality, Safety and Sustainability with
Smart, Innovative and Non-Destructive Technologies



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Integrating Sensor Fusion, Machine Learning, and Physics-Based Modelling for Predictive Shelf-Life Assessment of Apples in Cold Storage

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Abstract. Accurate prediction of shelf-life in cold-stored apples remains a complex challenge due to the interplay of physiological, biochemical, and environmental factors. This study develops an integrated computational framework combining dense sensor data acquisition, machine learning (ML) algorithms, and physics-based modeling to predict core temperature dynamics and shelf-life trajectories of Red Delicious apples over six months. The high-resolution dataset includes continuous measurements of temperature, humidity, and critical quality parameters such as total soluble solids (TSS), titratable acidity (TA), moisture, and weight loss. Core temperature prediction was achieved using extreme gradient boosting (XGBoost) and long short-term memory (LSTM) networks, with XGBoost outperforming LSTM by attaining an R^2 of 0.88. An entropy-based multi-criteria weighting methodology objectively ascertained the relative importance of multiple quality indices, emphasizing TSS and titratable acidity. Incorporation of a temperature and humidity modified Arrhenius equation provided an explicit mechanistic model for TSS degradation kinetics, capturing nonlinear decay trajectories under realistic storage conditions. Critically, hybrid modeling, integrating autoregressive lagged TSS features with ML-predicted core temperature and physics-modeled degradation rates yielded superior TSS prediction ($R^2 \approx 0.99$), underscoring the temporal autocorrelation and temperature dependencies essential for robust shelf-life estimation. However, inherent limitations include potential noise amplification in numerical differentiation of quality rates and assumptions of homogeneous storage conditions. Validation through time-series cross-validation protocols minimized information leakage and evaluated generalizability. This comprehensive approach demonstrates the feasibility of digital twin frameworks that fuse data-driven and mechanistic models for precision post-harvest management.

Keywords: apple cold storage, shelf-life prediction, core temperature, total soluble solids, machine learning, Arrhenius kinetics, digital twin, XGBoost, hybrid modeling

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1. Introduction

Post-harvest losses of fruits and vegetables represent a critical challenge to global food security, with estimates suggesting that approximately 20-30% of harvested produce is lost before reaching consumers (Singh et al., 2022). Apples, as one of the most economically important temperate fruits globally, require precise cold storage management to maintain quality and extend shelf-life. The complexity of predicting apple shelf-life stems from the intricate interactions among physiological processes, biochemical transformations, and environmental storage conditions (Farkas et al., 2024). Traditional quality assessment methods rely on periodic manual sampling and destructive testing, which are labor-intensive, time-consuming, and fail to capture the continuous dynamics of quality deterioration. Recent advances in digital twin technology have emerged as transformative tools for food storage systems, enabling real-time monitoring and predictive analytics throughout the supply chain (Verboven et al., 2020). Digital twins create virtual replicas of physical processes, integrating sensor data with computational models to simulate and predict system behavior. In postharvest agriculture, such systems promise to revolutionize quality management by providing continuous, non-invasive monitoring and early warning capabilities for quality degradation.

Machine learning applications in postharvest agriculture have gained substantial momentum, with researchers demonstrating the effectiveness of various algorithms for quality classification, defect detection, and shelf-life prediction (Chen et al., 2024; Kumari and Singh, 2025). Convolutional neural networks (CNNs) have shown remarkable success in image-based fruit quality assessment, achieving accuracies exceeding 99% in freshness classification tasks. However, most existing approaches focus on classification rather than continuous prediction of quality trajectories over extended storage periods. Recent studies on apple storage have emphasized the importance of precise environmental control, with research demonstrating that cultivar-specific storage protocols significantly impact quality retention (Allagui and Ben Amara, 2025; Watkins, 2018). For Golden Delicious apples, storage temperatures of 5-10°C with controlled humidity (85% RH) have been shown to influence physical and chemical properties over 10-week periods (Farkas et al., 2024). Red Delicious and other premium cultivars require even more stringent conditions, with temperatures maintained at 0-2°C and controlled atmosphere (CA) storage protocols involving specific oxygen and CO₂ concentrations (Watkins, 2018). While purely data-driven

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