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Dynamic shelf life: a new concept and direction for the 22nd-century poultry processing industry

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comment

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Posted Date: November 9th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11354620/v1

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Additional Declarations: No competing interests reported.

Article type: Comment

Title: Dynamic shelf life: a new concept and direction for the 22nd-century poultry processing industry

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Abstract

Poultry meat and eggs are highly perishable, yet their shelf life is still communicated through fixed dates that assume ideal storage conditions. Because the actual temperature, packaging, and handling history differs from one package to the next, a fixed date can overstate the quality of an abused product or force the disposal of one that is still safe and wholesome. This Comment proposes dynamic shelf life as a guiding direction for the poultry processing industry: the remaining shelf life of each product is estimated continuously from its measured condition and history rather than assigned once at packaging. The proposed framework links four layers. First, multimodal sensing during processing records the initial quality of carcasses, meat cuts, and eggs. Second, flexible smart-packaging sensors extend monitoring through cold storage, transportation, retail, and the household by tracking temperature, humidity, headspace gases, and spoilage volatiles. Third, explainable machine learning converts these data into freshness scores and remaining-shelf-life estimates that processors, retailers, and regulators can interpret and verify. Fourth, digital twins integrate this data stream into continuously updated virtual representations of products, batches, and cold chains, supporting decisions on stock rotation, routing, and discounting. Realizing this vision will require progress on sensor reliability and cost, validation under commercial conditions, evaluation of explanations and uncertainty, data governance, and regulatory

acceptance. Through interdisciplinary collaboration, dynamic shelf life could make poultry supply chains safer, less wasteful, and more transparent while keeping human decision-makers at the center.

Keywords: dynamic shelf life; poultry processing; smart packaging; multimodal sensing; explainable artificial intelligence; digital twins; cold chain; food waste

Background: the limits of a fixed date

The poultry industry is undergoing a rapid digital transformation, driven by rising expectations for food safety, quality assurance, traceability, sustainability, and supply-chain resilience. Yet the way shelf life is assigned has changed little. Quality is still judged largely through destructive sampling, laboratory analysis, visual inspection, and a single expiration date printed at packaging. These tools remain valuable, but they deliver isolated snapshots. They say little about how quality evolves during processing, packaging, storage, transportation, retail display, and household use.

This gap matters because poultry products deteriorate in response to their individual histories. Temperature abuse, moisture accumulation, microbial growth, lipid oxidation, gas production, and physical damage can progress unseen until spoilage becomes obvious. A fixed date, set under assumed storage conditions, cannot capture these differences. Products that experienced temperature abuse may spoil before the printed date, whereas well-handled products may be discarded while still wholesome. Field studies in poultry cold chains have already shown that monitoring at the level of the individual unit can support a flexible, or dynamic, shelf life and reduce waste [1], and decision systems combining predictive spoilage models with temperature monitoring were proposed for chilled foods more than two decades ago [2].

The idea of dynamic shelf life is therefore not new; what is new is the opportunity to realize it at scale. Advances in optical sensing, flexible electronics, Internet of Things (IoT) connectivity, machine learning

(ML), and cloud and edge computing now make it feasible to move from periodic assessment to continuous, connected, and predictive quality management [3]. However, two conditions must be met. First, accurate prediction alone is not enough: producers, processors, distributors, retailers, regulators, and consumers need to understand *why* a product is classified as fresh, deteriorating, contaminated, or unfit for sale. Second, sensing and prediction must span the entire value chain rather than operate as disconnected tools at individual stages. In this Comment, I argue that integrating multimodal sensing, smart packaging, explainable data science, and digital twins can meet both conditions and make dynamic shelf life a practical direction for the 21st-century poultry processing industry.

From processing line to consumer: continuous sensing and smart packaging

The proposed framework follows poultry products, including whole carcasses, cut-up and further-processed meat, and shell eggs, along a single value chain:

Farm → processing and quality inspection → smart packaging → cold storage → transportation → distribution → retail → consumer.

Although these products differ in composition and in how they deteriorate, they share this progression, and each stage offers a sensing opportunity. During processing, multimodal inspection systems can evaluate color, texture, chemical composition, internal structure, microbial contamination, and physical damage. Hyperspectral, fluorescence, near-infrared, thermal, X-ray, and conventional machine-vision imaging, together with gas sensors and biosensors, provide complementary physical, biochemical, structural, and microbiological information [3]. These measurements can support sorting, grading, and process control, and they remove defective products before packaging. Just as importantly, they establish each product's *initial quality*, which is the starting point for any shelf-life prediction.

Smart packaging then carries sensing beyond the plant into storage, transportation, retail, and the home (Fig. 1). A flexible, printable, multimodal sensor label could monitor temperature, relative humidity, pH, oxygen (O_2), carbon dioxide (CO_2), ammonia (NH_3), hydrogen sulfide (H_2S), and volatile organic compounds (VOCs). These variables reflect storage history, microbial metabolism, and the progression of spoilage in poultry meat. Measurements could be transmitted through Bluetooth Low Energy (BLE), near-field communication (NFC), long-range radio (LoRa), or Wi-Fi to edge devices, cloud databases, or smartphone applications.

The key principle is that sensing is not confined to a single stage. Data collected along the chain are linked progressively into a continuous product history. For example, imaging may characterize a chicken breast fillet or an egg at the processing plant, after which a package sensor tracks its temperature, gas composition, and volatiles throughout distribution. Together, these records reveal far more than either plant inspection or package monitoring could alone.

Explainable data science: from signals to decisions

Multimodal sensor data can be combined through statistical modeling, ML, deep learning, and data-fusion techniques to estimate product quality, detect contamination, classify spoilage risk, and predict remaining shelf life. Black-box models, however, offer little evidence for why they reach a decision. This opacity complicates scientific validation, troubleshooting, regulatory review, and stakeholder confidence, all of which are decisive in a food-safety context.

Explainable artificial intelligence (XAI) can reveal the relationships among sensor responses, product characteristics, storage conditions, and model predictions [4]. Feature-importance methods can show whether temperature, oxygen, pH, ammonia, specific spectral wavelengths, image regions, or storage duration drive a given prediction. Visual explanation methods can highlight the regions of a carcass,

fillet, or egg associated with defects or contamination. Such explanations let researchers test whether a model's reasoning is biologically and physically plausible rather than driven by spurious correlations.

Explainability also improves the system itself. Identifying the most influential variables can reduce the number of sensors required, lower cost, guide sensor placement, and improve computational efficiency, which are critical considerations for a low-margin, high-volume industry. Explanations can further help processors diagnose whether deterioration stemmed from inadequate chilling, package failure, excess humidity, microbial activity, or prolonged storage. Explainable data science should therefore not be treated as a visualization add-on; it is the bridge between sensor measurements and practical management decisions.

At the point of use, this intelligence could be presented through a smartphone or decision-support interface as package-specific freshness scores, spoilage warnings, microbial-risk estimates, and remaining-shelf-life predictions. Instead of assigning every package in a production batch the same conservative expiration date, each package could be managed according to its measured condition and actual history. This is the essence of dynamic shelf life.

Digital twins: the integrating layer

Digital twins represent the next stage of this intelligent poultry products system [5]. Here, a digital twin is a continuously updated virtual representation of a product, package, processing operation, storage environment, or supply-chain segment. It combines real-time sensor data, historical records, predictive models, process knowledge, and feedback mechanisms. Digital twins are increasingly investigated across agricultural production and agri-food supply chains, where they integrate sensing, prediction, simulation, and feedback to support monitoring, optimization, and decision-making [6–9].

A product-level twin of a poultry package might hold its initial quality, processing conditions, package atmosphere, temperature and humidity exposure, gas composition, predicted microbial growth, freshness status, and remaining shelf life. At larger scales, twins could represent processing lines, cold-storage facilities, refrigerated transport, or entire product lots moving through a distribution network. Information flows in both directions: data from the physical product update the virtual model, and predictions from the virtual model guide actions in the physical system. Data travel through IoT, edge, and cloud communication to data-fusion and XAI models; these models update the twin, which in turn supports quality prediction, spoilage detection, dynamic shelf-life estimation, traceability, and operational decisions, closing a continuous feedback loop to processing, storage, and distribution.

In practice, a twin might recommend adjustments to chilling temperature, package atmosphere, storage conditions, inventory rotation, distribution priority, or retail discounting. Products predicted to have a shorter remaining shelf life could be routed to nearby markets, further processed, or sold first, a "least shelf life, first out" policy, whereas products retaining high quality could enter longer distribution routes [1]. This human-centered cyber-physical approach aligns with the principles of Industry 5.0, pairing automated monitoring and prediction with interpretable information for human decision-makers. The aim is not to remove people from quality management but to give them timely, trustworthy intelligence that makes their decisions more consistent and effective.

Challenges and research priorities

The framework outlined here is a research direction, not a finished commercial system. Several scientific, engineering, and institutional challenges must be resolved before dynamic shelf life can be adopted widely.

- **Sensor robustness and practicality.** Sensor responses must remain reliable across variable humidity, temperature, lighting, packaging materials, and product compositions. Multimodal

systems must cope with differing sampling rates, missing measurements, sensor drift, and calibration variation. Package-integrated sensors must also meet requirements for power consumption, package compatibility, cost, recyclability, food-contact safety, and high-volume manufacturing.

- **Model updating and validation.** Digital twins require models that update continuously while remaining accurate across products, batches, facilities, and distribution environments. Validation protocols are needed to establish whether predictions remain reliable under commercial conditions, including how conservative safety margins should be set when a prediction overestimates shelf life [1].
- **Governance and acceptance.** Data ownership, cybersecurity, interoperability among supply-chain partners, regulatory acceptance of dynamic dating, and the clear communication of uncertainty to non-specialists all demand attention alongside the technology itself.

Three open questions deserve particular attention from the poultry science, food engineering, sensing, and data science communities:

1. Which combinations of sensing modalities provide sufficient information for reliable shelf-life prediction without making the system economically impractical?
2. How should explainability and uncertainty be evaluated for food-quality and food-safety decisions?
3. At what scale (individual product, package, batch, processing line, or whole supply chain) will digital twins deliver the greatest practical value?

Conclusion

The convergence of multimodal sensing, smart packaging, IoT connectivity, explainable data science, and digital twins could offer a pathway to transform poultry quality evaluation from isolated

measurement into continuous intelligence for the next century food systems. By following each product from processing through packaging, distribution, retail, and consumption while maintaining a dynamically updated record of its condition, the industry could replace the single printed date with a dynamic shelf life. The expected benefits include earlier detection of deterioration, package-specific shelf-life prediction, stronger traceability, smarter inventory management, less food waste, and more transparent quality decisions. Achieving this vision will require close collaboration among poultry and food scientists, agricultural and biological engineers, sensor and materials scientists, data scientists, supply-chain specialists, and regulators. Considerable research remains, but the framework proposed here provides a foundation for resilient, interpretable, and human-centered poultry supply chains that deliver safer, higher-quality food to consumers.

Abbreviations

BLE: Bluetooth Low Energy; CO_2: carbon dioxide; H_2S: hydrogen sulfide; IoT: Internet of Things; LoRa: long-range radio; ML: machine learning; NFC: near-field communication; NH_3: ammonia; O_2: oxygen; VOCs: volatile organic compounds; XAI: explainable artificial intelligence

Declarations

Ethics approval and consent to participate: Not applicable.

Consent for publication: Not applicable.

Availability of data and materials: Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

Competing interests: The author declares that he has no competing interests.

Funding: Not applicable.

Authors' contributions: AK conceived the concept, wrote and revised the manuscript, and read and approved the final manuscript.

Acknowledgements: Not applicable.

Use of large language models: During the preparation of this manuscript, the author used Claude (Anthropic) to assist with language editing and reference formatting. The author reviewed and revised all content and takes full responsibility for the article.

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Figure legend



Fig. 1 Conceptual smart-packaging system for real-time monitoring of the dynamic shelf life of processed poultry meat. A flexible, printable sensor label inside the package tracks temperature, relative humidity, pH, O_2, CO_2, NH_3, H_2S, and volatile organic compounds, and transmits the data wirelessly (BLE or NFC) to a smartphone application for real-time freshness monitoring and early spoilage detection.