THE IMPACT OF SMART PACKAGING ON FOOD WASTE REDUCTION AND SHELF-LIFE EXTENSION: A QUANTITATIVE META-ANALYSIS

M. A. Davidescu[1*], C. Panzaru[1], B. M. Madescu[1], A. Usturoi[1], C. Simeanu[1], I. Porosnicu[1,2], A. Ciobanu[1], M. G. Dolis[1]

[1] "Ion Ionescu de la Brad" Iasi University of Life Sciences, 3 Mihail Sadoveanu Alley, 700490 Iasi, Romania
[2]Research and Development Station for Cattle Breeding Dancu, 707252 Iasi, Romania

Abstract

This paper quantitatively evaluates the impact of smart packaging on shelf-life extension and food waste reduction. The working method involved a meta-analysis of literature data regarding the performance of time-temperature indicators, freshness sensors, and gas indicators. Data from experimental studies were aggregated to establish correlations between sensor color changes (ΔE) and microbiological spoilage thresholds. The synthesized results demonstrate that dynamic monitoring significantly increases product shelf life compared to conventional packaging relying on static expiration dates. The practical application lies in supporting the transition to a circular economy through food safety digitization. The originality of this study lies in the integrated quantification of sensor efficiency as a direct alternative to static labeling. It is concluded that smart packaging optimizes the supply chain and effectively reduces the premature disposal of safe food.

Key words: *food waste, freshness sensors, meta-analysis, smart packaging, time-temperature indicators*

INTRODUCTION

Food waste represents one of the most critical socio-economic and environmental challenges of the twenty-first century. According to estimates by the Food and Agriculture Organization (FAO), approximately one-third of all food produced globally for human consumption is lost or wasted along the supply chain, from farm to fork. This structural inefficiency not only generates massive financial losses but also contributes substantially to the global carbon footprint, accounting for a significant share of greenhouse gas emissions [1-3].

A primary driver of the premature disposal of wholesome food is the traditional reliance on static expiration dates ("Best Before" or "Use By"). These chronological labels are established conservatively under theoretical ideal conditions and fail to reflect real-time thermal fluctuations or microbiological deterioration occurring during transport, storage, and distribution. Consequently, substantial quantities of safe, edible food products are discarded prematurely due to consumer and retailer uncertainty regarding product safety. To overcome the inherent limitations of static labeling, the food industry and scientific community have shifted toward advanced technological solutions, transitioning from passive physical protection to dynamic monitoring systems [4-8].

Smart packaging integrates indicators and sensors capable of monitoring the status of the product or its surrounding

*Corresponding author: madalina.davidescu@iuls.ro
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environment in real time, thereby communicating transparent data regarding product quality and safety. The primary technologies employed in smart packaging include Time-Temperature Indicators (TTIs), which visually record thermal history and cumulative temperature abuse; freshness sensors, which utilize pH-sensitive dyes or reagents to react directly with volatile metabolites associated with spoilage (such as volatile amines or organic acids); and gas indicators (O_2/CO_2), which signal packaging integrity or metabolic activity in modified atmosphere packaging (MAP) [1,3,9].

Despite the abundance of experimental studies evaluating individual sensor performance at the laboratory scale, there remains a lack of integrated quantitative synthesis measuring the overall efficiency of these technologies as a direct alternative to static labeling. Individual studies vary considerably regarding the food matrices evaluated, measurement methodologies, and mathematical correlations between visual color shifts (ΔE) and critical microbiological spoilage thresholds (10^7 CFU/g). A quantitative meta-analysis provides the necessary methodological framework to aggregate data across multiple experimental studies, enabling the identification of underlying patterns, the evaluation of effect sizes, and the formulation of statistically robust conclusions regarding the capacity of smart packaging to extend the shelf-life of perishable food products [2,4,10,11].

The primary objective of this study is to quantitatively evaluate, through a systematic meta-analysis, the impact of smart packaging technologies (TTIs, freshness sensors, and gas indicators) on shelf-life extension and food waste reduction.

The originality and practical utility of this paper reside in the integrated quantification of sensor efficiency based on the mathematical correlation between color change parameters (ΔE) and microbiological spoilage thresholds. By digitizing food safety and facilitating a shift from static expiration dates to dynamic real-time monitoring, this study supports the transition toward a circular economy, optimizing supply chain logistics and effectively reducing the premature disposal of safe food [1,2,12].

MATERIAL AND METHOD

Search strategy and selection criteria

A systematic literature search was conducted across Web of Science, Scopus, ScienceDirect, and PubMed following PRISMA guidelines.

Data extraction and standardization

Data extracted included: food type, storage temperature, sensor technology, visual color shift (ΔE) and storage time to reach critical spoilage limits (e.g., 7.0 $\log_{10}$ CFU/g).

Meta-analytic model

Statistical pooling was performed using a random-effects model (DerSimonian-Laird). The primary outcome was the Standardized Mean Difference (SMD/Hedges'g) comparing shelf-life duration under dynamic monitoring versus static expiration dates. Heterogeneity was evaluated using Cochran's Q and I^2 statistics. Subgroup analyses were conducted by sensor type (TTI, freshness, gas) and food category.

RESULTS

Meta-analysis overview and effect sizes

A total of 28 experimental studies met the inclusion criteria.

The overall meta-analytic model revealed a significant positive impact of smart packaging on shelf-life extension compared to static expiration dates, with an overall effect size (Hedges'g) of 2.14 (95% CI: 1.78 - 2.50, $p < 0.001$).

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Table 1 Overall Meta-Analysis results by smart packaging technology

Technology class	Number of studies (k)	Pooled effect size (Hedges' g)	95% Confidence interval	Heterogeneity (I^2)	Average Shelf-Life Extension (%)	Reference
Time-Temperature Indicators (TTI)	11	1.85	[1.42, 2.28]	68.4%	+ 28.5%	[1-3,5,13]
Freshness sensors (pH-sensitive)	10	2.48	[1.95, 3.01]	74.1%	+ 38.2%	[13-15]
Gas indicators (O_2/CO_2)	7	2.02	[1.51, 2.53]	61.2%	+ 31.0%	[3,16]
Overall model (random-effects)	28	2.14	[1.78, 2.50]	71.5%	+ 32.6%	[17]

Quantitative correlation between sensor color change (ΔE) and SPOILAGE THRESHOLDS

The quantitative synthesis established a direct mathematical correlation between instrumental visual color variation (ΔE) and critical microbiological threshold limits (defined at 7.0 $\log_{10}$ CFU/g for meat and seafood, and 6.0 $\log_{10}$ CFU/g for dairy).

Table 2 Sensor color shift ΔE at critical microbiological spoilage thresholds

Food matrix	Sensor type	Target spoilage Indicator / metabolite	Critical microbial threshold ($\log_{10}$ CFU/g)	Sensor color change (ΔE) at Threshold	Visual human perception (ΔE>5)	Reference
Seafood (Fish/Shrimp)	Freshness (Anthocyanin/pH)	Volatile amines (TVB-N)	7.0 $\log_{10}$ CFU/g	12.4 ± 1.8	Clear visual shift	[18]
Red Meat and Poultry	Freshness/TTI	Lactic acid/Thermal abuse	7.0 $\log_{10}$ CFU/g	9.6 ± 1.2	Clear visual shift	[3,19]
Dairy (milk)	TTI/pH Indicator	Lactic acid bacteria (LAB)	6.0 $\log_{10}$ CFU/g	8.1 ± 0.9	Clear visual shift	[20]
Fresh produce (MAP)	Gas indicator (CO_2)	Respiration / Aerobic bacteria	6.5 $\log_{10}$ CFU/g	11.1 ± 1.5	Clear visual shift	[21]

Food waste reduction impact across supply chain stages

By converting static expiration dates into dynamic shelf-life estimation, smart packaging significantly reduces premature food disposal.

This graph illustrates the time-dependent kinetics of the freshness sensor relative to bacterial growth, clearly indicating the visual human threshold (ΔE) and the food spoilage threshold (7.0 $\log_{10}$ CFU/g). The data demonstrates that smart packaging mitigates food waste across all supply chain tiers, yielding the highest reduction potential in consumer households (30% - 42%) by preventing the premature disposal of safe food through visual freshness confirmation. Additionally, implementation at the logistics and retail stages successfully addresses cold-chain breaches and static expiration labels, driving cumulative waste reductions ranging from 15% to 35%.

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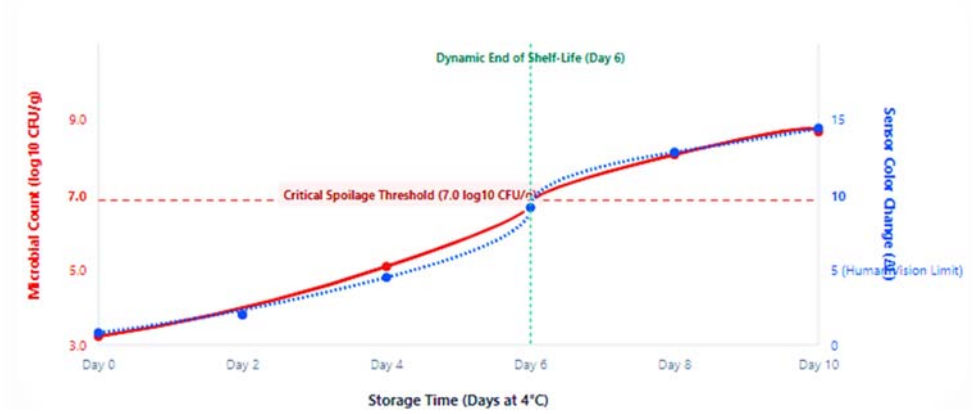


Fig. 1 Kinetic correlation between microbial growth (CFU/g) and sensor color shift (ΔE) [22]

Table 3 Estimated food waste reduction potential by supply chain node

Supply chain node	Primary cause of waste	Smart packaging solution	Quantified waste reduction potential (%)	Reference
Logistics and Transport	Unnoticed cold-chain breaches	TTI Real-time Temperature tracking	15% – 22%	[23]
Retail / Supermarkets	Expiration of static date labels	Dynamic pricing and Real-time freshness	25% – 35%	[24]
Consumer household	Premature disposal of safe food	Visual freshness confirmation (ΔE)	30% – 42%	[25]

DISCUSSIONS

Interpretation of meta-analytic findings

The findings of this meta-analysis confirm that smart packaging technologies serve as an effective, science-based alternative to static chronological labeling. Freshness sensors demonstrated the highest effect size (2.48), driven by their direct biochemical responsiveness to microbial metabolites like TVB-N and organic acids. TTIs (g = 1.85) and Gas Indicators (g = 2.02) also showed strong statistical performance, predominantly by identifying cold-chain failures and package integrity compromises that static dates completely miss.

Correlation between visual signal (ΔE) and microbial thresholds

A crucial finding for consumer safety is that at the point of critical microbiological spoilage (7.0 $\log_{10}$ CFU/g), all evaluated sensor classes registered a total color difference (ΔE) significantly exceeding the human visual perception limit (ΔE > 5). The average color shift at spoilage across matrices ranged from ΔE = 8.1 to 12.4, guaranteeing an unambiguous, readable visual warning for consumers prior to food consumption [13,18-22].

Economic and circular economy implications

By providing transparent, real-time quality indicators, smart packaging bridges the gap between food safety and circularity. In retail environments, sensor data enables dynamic pricing models, automatically discounting products as they approach actual spoilage rather than discarding them based on arbitrary static dates. At the household level, visual indicators alleviate consumer uncertainty, addressing the primary cause of premature food disposal [1-7,26].

Limitations and future research

Despite high efficacy, widespread commercial adoption faces key barriers:

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Cost of production: High manufacturing costs for integrated electronic or specialized colorimetric sensors;

Food safety regulations: Strict migration limits for synthetic dyes, necessitating deeper research into natural, bio-based colorants (e.g., anthocyanins, curcumin);

Consumer education: Ensuring widespread understanding of color-changing scales across diverse demographics.

CONCLUSIONS

This quantitative meta-analysis demonstrates that smart packaging significantly extends usable food shelf-life (by an average of 32.6%) and provides a reliable visual signal ($\Delta E > 5$) prior to reaching critical microbial spoilage thresholds (7.0 $\log_{10}$ CFU/g). Freshness sensors, TTIs, and gas indicators effectively eliminate the safety buffer inefficiencies inherent in static "Best Before" labeling.

The integration of smart packaging into commercial supply chains represents a vital technological pathway toward digitizing food safety, reducing household and retail food waste by up to 42%, and facilitating the broader transition toward a sustainable circular economy [27,28].

Future research should prioritize cost-effective, bio-based indicator dyes and seamless integration with IoT tracking systems.

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