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EVALUATION, MEASUREMENT AND STABILITY OF FRESH PRODUCT SHELF LIFE: IMPLICATIONS FOR REDUCING FOOD WASTE AND PROMOTING SUSTAINABLE FOOD PRODUCTION

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Abstract

This research analyses the assessment, quantification, and stability of fresh product shelf life, emphasizing their impact on food waste mitigation and sustainable food production. Given that food waste presents considerable environmental and economic concerns worldwide, it is essential to comprehend and enhance the shelf life of perishable goods. The research examines multiple evaluation techniques, such as shelf life testing, sensory assessments, and prediction modelling, to ascertain freshness and quality. Furthermore, it underscores the significance of sophisticated preservation methods, including active packaging and refrigeration technology, in prolonging shelf life and preserving product integrity. By enhancing shelf life, food makers, merchants, and consumers can more effectively manage stocks, decrease spoilage, and mitigate waste. This research seeks to enhance a sustainable food system by ensuring the delivery of fresh items to consumers while minimizing the ecological consequences of food waste.

Key words: *evaluation, food waste, shelf life, stability, sustainability.*

INTRODUCTION

Shelf life determination is a key aspect of food quality and safety assurance in putting safe and quality food on the market and also to assure a good food safety management. For an accurate estimation of foods shelf life, it is really important to first analyse the categories of food spoilage (physical, chemical and microbiological), the factors that influence the food spoilage and to identify the ways of controlling the food spoilage. Secondly, there is a need to identify the ways of measuring and predicting the shelf life and also to communicate it in order to raise awareness on food safety and also sustainability and food waste reduction.

Food waste represents a significant issue for society, with around 59 million tonnes being discarded annually across the European Union (https://food.ec.europa.eu/food-safety/food-waste_en).

In the context of food loss, the food industry generates significant amounts of byproducts each year during food processing. The most common are those derived from fruits and vegetables, which can be produced during pre-harvest and post-harvest stages, as well as throughout the preparation and processing phases.

These industrial by-products are very different from one another due to the difference in industrial processes (Nardella et al., 2022).

According to the European Commission, the main causes of food waste include a lack of awareness, poor shopping planning, confusion between "best before" and "use by" dates, and insufficient knowledge on how to make use of leftovers. Additionally, various studies have highlighted that a significant portion of household food waste results from preparing too much food and not consuming leftovers from previous meals (Lisciani et al., 2024).

Food waste is a pressing global issue, with implications that stretch across environmental, economic, and social dimensions. In industrialized nations, waste occurs at every phase of the food supply chain, starting from initial production losses on farms to consumer-end waste in retail environments. In the European Union alone, approximately yearly, the disposal of 59 million tons of food leads to significant resource loss, elevated greenhouse gas emissions, and numerous missed opportunities for feeding those in need. To tackle this challenge, a dual approach is required, addressing both upstream (production and processing) and downstream (retail and consumer) inefficiencies (Redlingshofer et al., 2017).

At the retail level, food waste is often driven by misaligned inventory management, overstocking, and conservative shelf-life settings for perishable items. Traditional fixed shelf life (FSL) labelling can lead to premature disposal, especially for highly perishable goods. As a solution, dynamic shelf life (DSL) models offer a more flexible approach by adjusting expiration dates based on real-time product quality indicators, which can be combined with discounting strategies to incentivize consumer purchases of near-expiration items. Together, DSL and discounting have the potential to reduce waste significantly while maintaining food safety and maximizing retailer profits (Buisman et al., 2019).

Simultaneously, addressing waste at earlier stages in the supply chain - specifically during primary production and processing - is critical. Food loss during these stages, often overlooked, can stem from natural factors like weather, handling practices, and stringent quality standards. For instance, in sectors like fruits, vegetables, and cereals, between 3% and 12% of food can be lost before reaching consumers, highlighting the need for efficient loss quantification and targeted intervention at the production level.

This study combines insights from DSL and discounting practices in retail with quantify-cation of production-stage losses in various food sectors, aiming to present a comprehensive strategy for food waste reduction. By examining these issues holistically, this research underscores the importance of integrated approaches that span the entire supply chain, supporting sustainable food systems and mitigating the negative impacts of waste on the economy and environment.

MATERIALS AND METHODS

This paper draws upon recent publications accessed through platforms such as Science Direct, Web of Science (via the Enformation platform), and Google Scholar. It also incorporates information from the websites of the Food and Agriculture Organization (FAO) and the European Food Safety Authority (EFSA), as well as national legislation from various countries related to the determination, assessment, and calculation of shelf life.

Additionally, two specific studies referring to (1) retail-level waste management through dynamic shelf life (DSL) and discounting strategies, and (2) quantification of food loss during primary production and processing stages were taken in the analysis. Combining these perspectives allowed us to give a holistic assessment of food waste reduction across the supply chain.

RESULTS AND DISCUSSIONS

1. Food spoilage: types and factors of influence

Food spoilage can have an important influence on food safety and quality and also the length of shelf life of foods (Basharat et al., 2022).

Physical spoilage refers to visible deterioration in food caused by factors such as physical damage, moisture loss or absorption, changes in texture, and other noticeable alterations in quality - often due to improper handling during storage, transport, or distribution. Fresh fruits and vegetables are particularly susceptible to such damage, which can occur as a result of poor respiration or chilling injuries during storage. Additionally, moisture transfer to or from food products can lead to spoilage and decay in many types of food (Roudaut et al., 2002). The low moisture content of powdered meals renders them very prone to absorbing moisture from their storage environment, resulting in an amorphous structure and causing the particles to adhere and form lumps. Crystal growth is another physical deterioration that can easily develop in food systems. The production of ice crystals from slow freezing or repeated freeze-thaw cycles in ice cream leads to a gritty texture in the final product (Ozmen & Langrish, 2002).

Chemical spoilage of food products can arise from the interaction of its chemical constituents or from their degradation influenced by factors such as temperature, water activity, pH, and storage conditions significantly influence food stability. The degradation caused by interactions between sugars and proteins can be classified into enzymatic and non-enzymatic processes. In fresh fruits and vegetables, enzymatic reactions may result in tissue softening and the formation of brown pigments. The deterioration of lipids in food might result from oxidation, enzymatic degradation, or other hydrolytic reactions. In hydrolytic rancidity, the fatty acids separate from triglycerides due to the reaction of lipolytic enzymes in the presence of water. The resulting shorter-chain fatty acids tend to have a weaker flavor and can sometimes produce a rancid smell. These reactions typically take place at high temperatures, generally above 60°C, and can be prevented by reducing the exposure of lipid molecules to moisture (Kilcast & Subramaniam, 2000).

Microbial spoilage constitutes a prevalent and critical category of deterioration in all food kinds. It constitutes around 25% of global food loss and is associated with numerous foodborne illnesses (Bondi et al., 2014). A variety of microorganisms are recognized as agents of food deterioration and significant foodborne illnesses. Typical instances comprise *Escherichia coli*, *Listeria monocytogenes*, *Salmonella* spp., *Bacillus cereus*, *Campylobacter jejuni* and *Vibrio* spp. (Șuler et al., 2021) The incidence of food spoiling due to bacteria is significantly elevated, particularly in high-protein foods such as fish, dairy, and meat products (Petruzzi et al., 2017; Postolache et al., 2023). *Rhizopus* spp., *Aspergillus* spp., *Penicillium* spp., and *Fusarium* spp. are the primary molds responsible for food deterioration, with certain *Aspergillus* species creating aflatoxins that contribute to foodborne sickness.

Food spoilage typically arises from both intrinsic properties of the food and diverse environmental influences. Raw foods possess inherent resistance against microbial infestation owing to the robust structure of their exteriors (such as fruit and vegetable peels, shells, and bran). Nonetheless, these goods sustain physical damage during many processing processes and are susceptible to microbial infestation and deterioration caused by enzymes (Petruzzi et al., 2017).

Foods high in sugar are typically susceptible to fermentative germs, while those rich in protein and fat are more likely to be affected by proteolytic and lipolytic microbes, respectively (Modi, 2009). Some spoiling reactions are catalysed by the presence of diverse metal ions and other trace elements. Conversely, the existence of several naturally occurring antimicrobial substances in foods might impede or diminish spoiling rates, hence prolonging product shelf life (Davidson & Critzer, 2012). Lysozyme found in egg albumin disrupts the cell walls of Gram-positive bacteria and inhibits protein breakdown. Additional antimicrobial food constituents that impede the proliferation of spoilage microorganisms include nisin, sorbates, citrate, butylated hydroxyanisole, benzoates, and sulphur dioxide (Jeantet et al., 2016).

Water activity (a_w) is defined as the ratio between the vapor pressure of a given substance and that of pure water under the same conditions. Most bacteria thrive in an optimal water activity range of 0.995 to 0.98. A minor decrease in water activity within the food system, either through moisture reduction or the incorporation of salt, sugar can significantly inhibit microbial development and substantially extend its shelf life. Bacteria often necessitate elevated water activity for growth and are not easily supported in desiccated food products (Modi, 2009).

pH quantifies the concentration of hydrogen ions in a substance, correlating to its acidity level. Each microbe possesses an optimal pH range for its development and metabolic functions: most of bacteria proliferate at neutral pH range (Jeantet et al., 2016), yeasts can proliferate within a pH range of 4.5-7.0, with certain species capable of thriving in a pH range of 2.0-2.5 (Modi, 2009).

Each microorganism grows within a specific temperature range, reaching its highest growth rate at its optimal temperature. Bacteria are classified as psychrophiles, mesophiles, or thermophiles, with optimal growth temperatures of approximately 12-15°C, 30-45°C, and 52-75°C, respectively. The lag phase of microbial development often diminishes as temperature rises, facilitating enhanced growth in future periods. A greater temperature concurrently influences various enzyme activity and protein synthesis, hence impacting the product's shelf life. Yeasts and molds, conversely, may proliferate readily at or below ambient temperature and are frequently responsible for the deterioration of food stored in cold and chilly environments (Modi, 2009). Bacterial and fungal spores are regarded as the most heat-resistant species, with some enduring temperatures exceeding 100°C (Jeantet et al., 2016).

2. Evaluation, detection and identification of food spoilage

Food spoilage refers to the decline in nutritional value, sensory qualities, and overall safety of food, making it unsuitable for consumption. To prevent spoilage, it is essential to understand the microorganisms responsible and to implement various systems, methods, and technologies. At the industrial level, spoilage is managed or detected through the application of the Hazard Analysis Critical Control Point (HACCP) system, along with efficient production practices and thorough risk assessments (Panisello & Quantick, 2001). Heat, packaging, processing, and storage for food preservation diminish the likelihood of spoiling causes in the environment.

The detection and identification of spoiling are critical criteria in contemporary food industries due to health hazards linked to the consumption of infected foods are potentially fatal.

Biosensors are analytical devices that integrate a biological recognition element with a physicochemical transducer for the detection of specific chemical substances. Recent methodologies have employed enzymatic reactor systems coupled with amperometric electrodes to quantify diamine concentrations, thus enabling the evaluation of meat quality, particularly in beef, fish, and poultry. Postmortem enzymatic activity further contributes to the degradation of muscle tissue. Moreover, advanced biosensing platforms based on nucleic acid probes (DNA or RNA), mass spectrometry, bioluminescence, and related technologies are currently under development for the rapid and accurate detection of bacterial contamination in food products (Freitas et al., 2011); nevertheless, progress in mold detection remains limited.

Microbial metabolites serve as possible indicators for detecting food decomposition in meat products. After bacteria have utilized surface-level glucose, they will subsequently metabolize various substrates, including free amino acids. To do this, numerous bacteria excrete various proteolytic enzymes, with Gram-negative bacteria mostly releasing amino peptidases at refrigeration temperatures on meat (Basharat et al., 2022). Numerous researchers have suggested that the involvement of enzymes may be swiftly utilized using enzyme assays to assess beef stability about bacterial counts. The synthesis of amines, ammonia, indoles, and other pH-lowering chemicals further exacerbates deterioration due to amino acid consumption.

A developed tool is the nucleic acid-based detection of spoilage microorganisms, referred to as polymerase chain reaction (PCR). This technique identifies many gene sequences that specifically assist in detecting rotting microorganisms. The application of PCR-based typing techniques, including microsatellite PCR fingerprinting and random amplified polymorphic DNA (RAPD) analysis (Basharat et al., 2022), enables the differentiation of individual spoilage strains, regardless of species, and facilitates the identification of their sources of origin (Basharat et al., 2022). A listing for this kit for the identification of fungi in food by DNA fingerprinting is found in Fung (2002); however, no recent activity regarding its recognition is reported. A DNA-based approach for detecting molds in food may become commercially viable with additional development.

Spoilage can be identified through alterations in organoleptic qualities, including changes in odor, the presence of visible microflora colonies, surface stickiness of meat, and variations in flavor. The alterations in organoleptic odor are currently assessed by electronic noses and have shown highly effective in the evaluation of meat and fish (Gardner & Bartlett, 2000). The identification of volatiles as an indicator of mold growth was utilized in the development of electronic noses. Söderström et al. (2003) conducted an experiment to measure mold development in malt extract solution via an electronic tongue, akin to an electronic nose, which has several metal sensors that detect non-volatile substances in liquid.

3. Modern Measurement Techniques

Accelerated Shelf Life Testing (ASLT)

ASLT involves subjecting products to intensified stress conditions - such as elevated temperature and humidity - to speed up the degradation process. The data obtained is then analyzed using the Arrhenius equation to estimate the product's shelf life under typical storage conditions (Calligaris et al., 2019). For instance, a product stored at 40°C for 3 months may simulate 12 months of shelf life at 25°C.

Predictive Modelling

Predictive models use mathematical equations to forecast shelf life based on degradation kinetics. Common models include zero-order, first-order, and Weibull kinetics. Software tools, such as ComBase and Pathogen Modeling Program (PMP), integrate microbial growth and chemical reaction data to predict shelf life (Cakmak, 2019).

Non-Destructive Techniques

Non-destructive methods allow real-time monitoring without altering the product: Near-Infrared Spectroscopy (NIRS): Measures chemical composition and moisture content; Electronic Noses (E-Noses): Detect volatile compounds indicative of spoilage; Magnetic Resonance Imaging (MRI): Visualizes internal structural changes.

Biosensors and Smart Packaging

Biosensors detect specific biomarkers of spoilage, such as pH changes or microbial metabolites. Smart packaging incorporates indicators (e.g., time-temperature indicators, freshness sensors) that provide real-time information on product quality (Yam et al., 2005).

4. Predicting shelf life

Predicting shelf life accurately is crucial for minimizing food waste and ensuring food safety and quality. It involves using various scientific methods and models to estimate the time a food product remains acceptable for consumption.

This prediction is based on different methods based on different factors that influence the shelf life (based on water activity, pH, nutrient content, enzyme activity, food matrix and food structure and antimicrobial compounds, temperature, humidity, light exposure). These are real-time storage studies and accelerated shelf life tests which are time and resource consuming (Chanpet et al., 2020).

The traditional methods depend on sensory assessment, expertise, and historical information. Although beneficial, they are inherently subjective and lack precision. Accelerated shelf life studies subject the food to more severe circumstances (e.g., elevated temperatures) than typical storage practices. The observed degradation rates are extrapolated to forecast shelf life under standard storage circumstances. This is predicated on the assumption that the degradation mechanisms adhere to Arrhenius kinetics (www.hemdahl.com).

Predictive microbiology models employ mathematical frameworks to characterize the proliferation of microbes under certain parameters (temperature, pH, aw, etc.). These models can use intrinsic and extrinsic elements to mimic microbial development and forecast the duration required to attain a given spoiling level (e.g., a designated microbiological count or sensory threshold) (Stavropoulou et al., 2019).

Kinetic modelling of chemical reactions akin to predictive microbiology, simulates the pace of chemical reactions that lead to food degradation (e.g., oxidation, enzymatic processes). These models are employed to forecast alterations in food quality characteristics (e.g., color, flavor, texture) across time (van Boekel, 2009).

Machine learning and artificial intelligence: These sophisticated methodologies may evaluate extensive datasets of intrinsic and extrinsic variables alongside observed shelf life data to construct predictive models. They can discern intricate correlations between variables and shelf life, which are challenging to encapsulate using conventional models. Algorithms such as support vector machines (SVMs), neural networks, and random forests are frequently employed (Shi et al., 2023).

5. The design of shelf life experiments

The ideal approach to sensory testing involves assessing all samples from each storage condition and time point simultaneously within a balanced design. This can be achieved in three different ways. First, samples can be collected from successive production batches and stored for a specific period. Once they reach the end of their shelf life, all samples can be evaluated together using an appropriate testing setup (Figure 1). However, this method is susceptible to variations in production quality and is only suitable when production consistency is assured (Kilcast et al., 2000).

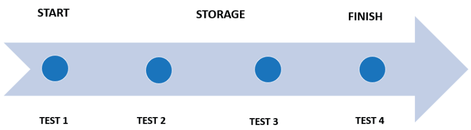

Figure 1. A shelf life testing strategy based on a partially staggered design

Another version is conducted wherein a single large batch is maintained under circumstances that ensure negligible quality alterations, such as frozen storage. Samples are extracted at specified intervals and preserved under optimal conditions (Figure 2).

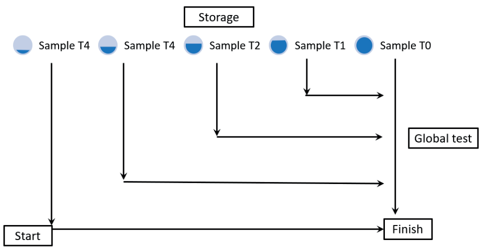

Figure 2. Simple design for shelf life testing

The third form (Figure 3): a significant batch is preserved, and samples are retrieved at specified intervals and kept under stable conditions (e.g., frozen) until the necessary storage period is fulfilled. The primary challenge in the latter two designs lies in determining suitable stable storage conditions, given that most food products cannot be stored for extended periods without significant changes in quality attributes. While all three methodologies offer the substantial benefit of delivering an internally consistent depiction of changes in sensory attributes, they are impeded by several limitations. Initially, no data regarding stability and shelf life is generated until the completion of storage studies, a situation unlikely to be tolerated in most industrial environments. Secondly, initiating the trials requires prior knowledge of the expected shelf life. Thirdly, a worldwide assessment may pose considerable logistical difficulties for instrumental laboratory measurements (Kilcast et al., 2000).

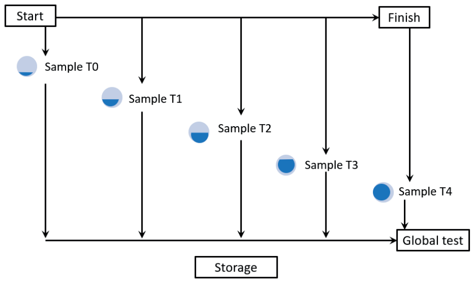

Figure 3. Another design for shelf life testing

6. Retail-Level Waste Reduction Through Dynamic Shelf Life (DSL) and Discounting

The implementation of dynamic shelf life (DSL) systems at the retail level has demonstrated significant potential for reducing food waste, particularly for highly perishable items. DSL operates by adjusting expiration dates in real time, based on factors such as temperature and product quality, allowing retailers to keep products on shelves longer when conditions permit. This flexibility contrasts with fixed shelf life (FSL) systems, which often lead to early disposal due to conservative expiration settings (Redlingshofer et al., 2017).

Key results from the simulation model reveal that DSL:

- Reduces Waste by Extending Usable Shelf Life: Compared to FSL, DSL allowed products to stay on shelves longer, resulting in a 10-20% decrease in waste. (Stenmarck et al., 2016). By continuously assessing product quality, DSL ensures that products are disposed of only when they no longer meet safety standards.
- Increases Retail Profitability: With DSL, retailers experienced a profit increase due to fewer losses and improved stock turnover. Profit gains were especially notable when DSL was paired with discounting, which encouraged consumers to purchase near-expiration items.
- Reduces Stock Shortages and Improves Inventory Planning: DSL's adaptability enabled

more accurate replenishment, helping retailers avoid overstocking and unexpected stock-outs.

Discounting further enhanced these outcomes by aligning with consumer purchasing behavior. Products near expiration were marked down, making them more attractive to price-sensitive customers. The combined use of DSL and discounting resulted in optimal reductions in waste while preserving or even boosting retailer profits (Buisman et al., 2019).

Overall, these findings suggest that DSL, particularly when coupled with targeted discounting, provides a robust framework for minimizing waste and maximizing sales of perishable goods. Retailers can adjust these strategies based on seasonal demand and product type, further supporting inventory flexibility.

7. Quantification of Food Losses in Primary Production and Processing

The quantification of food losses at the stages of primary production and processing reveals considerable waste across diverse segments of the food system, underscoring critical intervention points for improving efficiency and sustainability.

- Fruits and Vegetables: Losses in this sector were the highest, averaging up to 12%. Contributing factors include handling damage, spoilage from delays, and high grading standards that lead to the discard of visually imperfect items.
- Cereals and Pulses: Loss rates for cereals and pulses were between 3% and 7%. Losses were often due to environmental factors such as weather variability, as well as handling and storage practices.

The findings indicate that food losses vary widely depending on the type of product and processing requirements, suggesting that sector-specific waste reduction measures are essential. Improving handling practices, upgrading storage facilities, and adjusting visual quality standards could significantly reduce waste, particularly for fresh produce.

8. Recycling and Reuse as a Supplementary Waste Reduction Strategy

The study also highlights the importance of recycling and reuse to minimize waste across the supply chain. When products are unsuitable for direct consumer sales but still safe for consumption, they are often diverted to animal feed or food donations. Expanding food donation programs, particularly for fruits and vegetables, could further reduce food loss while supporting communities in need. However, the effectiveness of these efforts depends on well-coordinated logistics and partnerships between producers, retailers, and charitable organizations.

The main goal in preventing food waste should be to take action directly at the source by reducing the production of surplus food at every stage of the food supply chain - namely production, processing, distribution, and consumption. When this is not possible, the next best preventive measure, aligned with the waste hierarchy and aimed at maximizing the value of edible food, is to redirect surplus food for human consumption, provided it is safe to do so. As part of the Circular Economy Action Plan, the European Commission has introduced EU guidelines on food donation to support the recovery and redistribution of safe, edible food to people in need. These guidelines, developed in collaboration with the EU Platform on Food Losses and Food Waste, aim to:

- Support both food donors and recipients in complying with EU regulations (including those on food safety, hygiene, traceability, liability, and VAT);
- Encourage a consistent interpretation of EU rules across Member States regarding the redistribution of surplus food. (https://commission.europa.eu/index_en) (Figures 4 and 5).

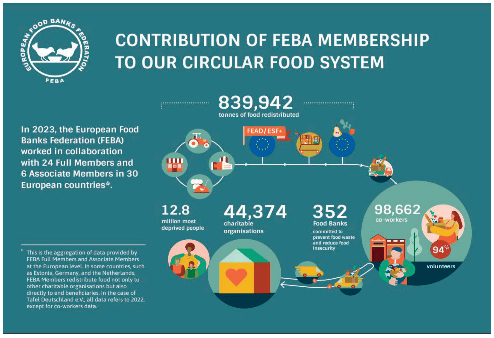

Figure 4. Contribution of FEBA as supplementary waste reduction strategy.
Source: https://www.eurofoodbank.org

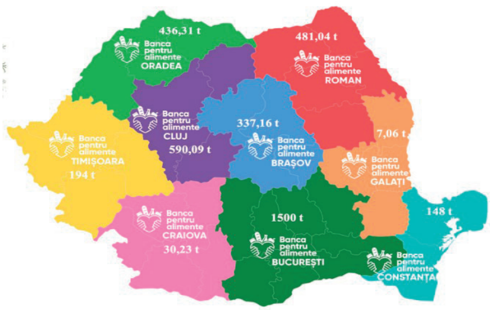

Figure 5. Network of Food Banks in Romania and the quantities (tons) of food collected in 2021. Source: https://rocesp.ro/

9. Integrated Impact Across Supply Chain Stages

By combining DSL and discounting strategies at retail with quantification of production-level losses, this study provides an integrated approach to reducing waste across the food supply chain. While DSL and discounting address waste at the consumer end, quantifying early-stage losses in production and processing enables targeted interventions for specific sectors. For example, introducing better storage and handling methods at the production level can help ensure that produce reaches retailers in optimal condition, reducing waste before it even reaches the shelf.

This integrated strategy reveals that effective food waste management must span the entire supply chain, from production to consumer. Retail interventions like DSL and discounting are valuable for perishable items close to the point of sale, while improvements in primary production can help prevent waste upstream. Together, these findings suggest that combining downstream and upstream approaches can maximize food waste reduction across diverse food categories (Buisman et al., 2019).

CONCLUSIONS

Extending the shelf life of fresh products is essential for reducing food waste and advancing food sustainability. This study demonstrates that dynamic shelf life (DSL) systems, especially when combined with discounting, can significantly decrease waste in retail by adjusting expiration dates based on real-time quality assessments. DSL allows retailers to maintain products on shelves as long as they are safe, preventing premature disposal and increasing profitability. For highly perishable items like fruits, vegetables, DSL enhances inventory flexibility, reducing the risks of spoilage and overstocking.

Beyond retail, addressing waste during production and processing stages is critical. Quantifying these losses identifies areas where improved handling, storage, and grading standards can reduce waste at the source, ensuring that more fresh products reach consumers. Integrating DSL with early-stage loss prevention supports a more sustainable food system, conserving resources, reducing emissions, and enhancing food security. Moving forward, innovations in shelf life extension and consumer acceptance of “imperfect” produce will be vital for a circular, sustainable food economy focused on minimizing waste from farm to table.

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