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Extending Freshness at Home: A Critical Review of Shelf-Life Technologies for Fruits and Vegetables

Carolin Heidloff & Astrid Klingshirn

Abstract

Fresh fruits and vegetables are among the most frequently discarded food items in households. This study evaluates technical solutions for extending shelf life based on criteria such as functionality, everyday usability, and sustainability. The focus lies on market-ready approaches that are accessible and available to consumers. Particularly effective is the combination of temperature control and reusable packaging. Additional potential is offered by active systems such as ethylene absorbers or air filters, although their effectiveness is product-specific and requires further analysis in real household settings. Regardless of technological solutions, consumer responsibility - through proper handling and proactive consumption planning - remains essential.

Keywords: Shelf-life extension, Food waste, Household technologies, Freshness preservation, Ethylene control

Verlängerung der Frische zu Hause: Eine kritische Bewertung von Technologien zur Verlängerung der Haltbarkeit von Obst und Gemüse

Kurzfassung

Frisches Obst und Gemüse zählen zu den am häufigsten entsorgten Lebensmitteln in Haushalten. Diese Studie bewertet technische Lösungen zur Haltbarkeitsverlängerung anhand von Kriterien wie Funktionalität, Alltagstauglichkeit und Nachhaltigkeit. Im Fokus stehen dabei marktreife und für Verbraucher verfügbare Ansätze. Besonders wirksam ist die Kombination von Temperaturkontrolle und wiederverwendbaren Verpackungen. Ergänzende Potenziale bieten aktive Systeme wie Ethylenabsorber oder Luftfilter, deren Nutzen jedoch produktspezifisch ist und weiterer Analysen im Haushaltskontext bedarf. Unabhängig von technologischen Ansätzen bleibt die Verantwortung des Verbrauchers – im sachgerechten Umgang und in der vorausschauenden Verbrauchsplanung – wesentlich.

Schlagwörter: Haltbarkeitsverlängerung, Lebensmittelverschwendung, Haushaltsnahe Technologien, Frischeerhalt, Ethylenmanagement

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Introduction: The Challenge of Food Waste in Private Households

Food waste is one of the major challenges of our time, from ecological, economic, and ethical perspectives alike. Despite growing awareness of sustainability and resource conservation, enormous quantities of food are still thrown away annually worldwide. In Germany alone, according to data from the Federal Ministry of Food and Agriculture (BMEL), approximately 11 million tons of food are wasted annually, with around 58 % of that originating directly from private households. This makes everyday consumers the largest source of food waste, ahead of industry, retail, and gastronomy (BMLEH 2024).

A significant portion of these losses involve fresh, highly perishable products such as fruits and vegetables. According to data from the Thünen Institute, they account for around one-third of all food discarded in households (Thünen-Institut 2023). The reasons for this type of waste are diverse: improper storage conditions, excessive purchase quantities, misjudgement of freshness, or a lack of knowledge about shelf life and suitable storage methods. Additionally, consumers are increasingly accustomed to visually perfect food products and often tend to discard items at the first sign of minor quality defects, even when they are still edible (Herzberg et al. 2020, Secondi et al. 2015, Klingshirn et al. 2022).

Food waste not only represents a loss of edible resources but also contributes to environmental pressures. Fresh produce that is discarded after purchase has already required inputs such as water, energy, agricultural land, labour, and transport. Its disposal further increases greenhouse gas emissions, including methane from organic degradation in landfills. Avoiding household food waste can therefore help reduce resource consumption and minimize climate-relevant emissions (Umweltbundesamt 2015).

Against this background, technical innovations aimed at spoilage prevention and shelf-life extension are increasingly coming into focus for researchers, industry, and consumers. While temperature control, smart packaging technologies, and hygiene management have long been standard in professional food processing—especially in combined application—equivalent solutions are gaining importance in private households. The market is offering a growing variety of products specifically tailored to the needs of end consumers, ranging from specialized storage containers to ethylene filters and air purification systems (Douaki et al. 2024).

This increasing diversity is accompanied by a multitude of product claims and preservation mechanisms that are often difficult for consumers to assess. The lack of independent validation and standardized performance metrics makes it challenging to distinguish between truly effective solutions and marketing-driven promises (Petersen et al. 2023). As a result, many consumers face uncertainty when selecting appropriate freshness-preserving technologies for everyday use.

The aim of this paper is to provide a structured and evidence-based overview of technologies currently available to extend the shelf life of fruits and vegetables in private households. Building on a comprehensive literature review and a structured screening of consumer-oriented offerings, the study identifies and evaluates both established and emerging solutions. In addition to temperature control as a standard physical preservation method, packaging solutions, air treatment systems, and antimicrobial technologies are considered. The focus lies on consumer-accessible systems that are easy to integrate into everyday routines. Using a multi-criteria evaluation matrix, the paper systematically assesses each approach in terms of functional plausibility, usability, hygiene, sustainability, and cost-efficiency. A categorized overview of representative product types complements the analysis and illustrates the diversity of available solutions. The goal is not only to describe the technical principles behind these innovations but to critically assess their real-world relevance, effectiveness, and value for end users.

Spoilage Mechanisms: Why Fresh Produce Deteriorates

Fresh fruits and vegetables remain metabolically active even after harvest. Deprived of the plant's supply system, they begin to degrade internal reserves, resulting in quality loss and eventual spoilage. Spoilage encompasses physical, chemical, and microbiological changes that render food unfit for consumption. Temperature-sensitive products - such as berries and leafy greens - are particularly prone to deterioration when not stored appropriately. Common symptoms include discoloration, dehydration, textural degradation, and microbial infestation (Brennike & Schopfer 2010, Barth et al. 2009).

Key physiological and physicochemical processes continue post-harvest, notably respiration. In this process, stored carbohydrates are converted into carbon dioxide and water, accelerating ripening and senescence. High respiration rates correlate with faster deterioration. Climacteric fruits, such as apples and bananas, emit ethylene during ripening, a plant hormone that further accelerates maturation—affecting not only the fruit itself but also nearby sensitive produce in shared storage environments.

Enzymatic reactions also contribute to spoilage. Polyphenol oxidase initiates enzymatic browning, while pectinolytic enzymes degrade cell wall components like pectin, leading to tissue softening and structural loss. These changes compromise both sensory quality and microbiological stability (Kader 2013).

Microbial spoilage is primarily caused by bacteria, yeasts, and molds. High water activity, combined with surface damage, creates ideal conditions for colonization. Warm temperatures and elevated humidity exacerbate microbial growth. Common spoilage organisms include *Botrytis cinerea* (gray mold), *Penicillium spp*., and *Pseudomonas spp*. These microbes induce decay, produce slime, initiate unwanted fermentations, or generate hazardous secondary metabolites such as mycotoxins (Vaclavik et al. 2008b).

Household Habits and Storage Practices: Drivers of Freshness Loss

While losses along the supply affect around 30-50 % of global fruit and vegetable production, studies show that losses in final consumption play a dominant role, particularly in industrialized countries. According to FAO and BMEL data, more than half of avoidable food losses occur in private households. Fruit and vegetables account for the largest proportion of these avoidable food loss. In addition to product-specific causes of spoilage, it is primarily consumer-related factors that promote the rapid loss of quality after purchase. The handling of fresh produce at home is therefore a central link in the food chain that plays a key role in determining shelf-life and waste (FAO 2023, BMLEH 2024b).

A critical point is the interruption of the cold chain. Even during transportation from the supermarket to home, sensitive products such as berries, lettuce or herbs can be damaged by high ambient temperatures (Kranert 2012).

How consumers store food plays a crucial role in preserving product quality and preventing premature spoilage. Although most households are equipped with refrigerators, pantries, or cellars, fruits and vegetables are often kept under suboptimal conditions. A lack of knowledge about ideal storage temperatures - particularly for chill-sensitive produce - as well as inadequate control of humidity levels and poor understanding of produce compatibility frequently lead to quality degradation. Common mistakes include overfilling the refrigerator, obstructing air circulation, and placing sensitive items in the door compartments, where temperatures tend to fluctuate and are generally too warm. Additionally, storing produce in sealed plastic bags without ventilation, leaving damaged or cut fruit uncovered, or placing delicate items in lower compartments - where humidity is often excessive - can significantly accelerate spoilage (BMLEH 2021, Freitag-Ziegler 2025, Klingshirn et al. 2022).

Proper storage practices can significantly extend the freshness of fruits and vegetables. Research highlights the importance of temperature and humidity control, especially for perishable items such as leafy greens or berries (Wucher et al. 2021). Maintaining the cold chain from purchase to home storage is equally critical, as even short exposures to ambient temperatures can reduce shelf life (Kranert 2012). Furthermore, the interaction between several types of produce must be considered: climacteric fruits like apples and bananas emit ethylene, a natural ripening hormone that can accelerate spoilage in ethylene-sensitive items. However, under refrigerated conditions, ethylene synthesis and activity are significantly reduced, making its impact in household settings less critical than often assumed (Saltveit 1998, Kader 2013, Klingshirn et al. 2022).

or instance, tropical and fruit vegetables such as cucumbers, tomatoes, and peppers are sensitive to chilling and should not be stored below 10°C, as low temperatures can cause texture degradation and flavor loss. In contrast, root vegetables like carrots and potatoes benefit from cool, dark, and humid conditions to maintain freshness and prevent sprouting or drying out. The use of breathable storage materials, such as cloth bags or ventilated containers, can help regulate moisture and prevent mould. Moreover, separating ethylene-producing from ethylene-sensitive items, even within the fridge, can further reduce spoilage risks (Freitag-Ziegler 2025). Yet, the impact of ethylene should not be overstated: under refrigerated conditions, ethylene synthesis is significantly reduced, and its effect on neighbouring produce is limited (Saltveit 1998, Kader 2013).

In addition to physical storage conditions, household organization plays a key role. Many losses result from forgotten items or overstocking. Applying the "first in, first out" principle and regularly checking stored food can help reduce waste (Secondi et al. 2015). Overall, consumer education on proper storage techniques, combined with simple tools and structured routines, is essential for extending the shelf life of fresh produce and minimizing household food waste (Garcia-Garcia et al. 2017).

Technological solutions for extending shelf-life in the household sector

Various technological approaches are available for the domestic preservation of fresh fruits and vegetables. These solutions encompass a broad range of methods, from well-established storage techniques to more recently developed systems. Their implementation and functional principles differ according to technical design, product-specific requirements, and usage conditions. The following overview outlines selected technologies that are currently used or under consideration in the household context:

- **Temperature Control:** Controlling storage temperature is a central measure in postharvest handling. Refrigeration and freezing slow down enzymatic activity, microbial proliferation, and respiration rates, which are key factors influencing ripening and spoilage (Vaclavik & Christian 2008a, Fu & Labuza 1993).
- **Packaging Solutions:** Packaging materials and designs can act as physical barriers to environmental influences such as oxygen, moisture, or microorganisms. Common household options include reusable containers, beeswax wraps, and silicone bags. Their effects on produce quality depend on the type of packaging, the stored product, and the surrounding conditions (Hussain et al. 2024, Kumar et al. 2022).
- **Refrigerator Filter Systems:** Some household refrigerators are equipped with integrated filter components, such as activated carbon or mineral-based inserts. These systems are designed to reduce ethylene concentrations, odours, or humidity, thereby aiming to create more stable storage environments (Stream Peak 2024, Ebrahimi et al. 2021).
- **Ethylene Absorbers:** Ethylene control technologies function by binding or neutralizing this plant hormone, which influences the ripening of climacteric fruits. These absorbers are available in various formats and are intended for use in mixed or ambient storage conditions (Stream Peak 2024, Kumar et al. 2024).
- **Edible Protective Coatings:** Edible coatings form a thin, semi-permeable layer on the surface of fresh produce. By modulating gas exchange and moisture transfer, such coatings are investigated for their potential to influence shelf-life and quality parameters. Their application in the domestic setting is currently limited (Hussain et al. 2024, Panchal et al. 2022).
- **Further Innovations:** Additional household-oriented approaches include ozone-based devices, gas-phase treatments, and visual freshness indicators. These technologies target specific spoilage-related processes or hygiene aspects and are the subject of ongoing research regarding their applicability in home use (Lisboa et al. 2024, Dubey et al. 2024).

Methodology

This study follows a structured methodological framework to identify, analyse, and evaluate technological innovations aimed at extending the shelf life of fresh fruits and vegetables in private households. The research process consists of two main phases: a scientific literature review and a structured market analysis.

In the **first phase**, a systematic search is conducted using academic databases such as ScienceDirect, SpringerLink, Wiley Online Library, and Google Scholar. Search terms include combinations of English and German keywords such as "shelf-life extension", "fruit and vegetable storage", "ethylene control", "household food preservation", "Kühlschrankfilter", and "Frischhalteverpackung". Only peer-reviewed articles and review papers published between 2008 and 2025 are considered to ensure scientific relevance and state-of the art approaches.

The **second phase** involves a structured screening of the consumer market. This includes product databases (e.g. Amazon, Kaufland, IKEA), manufacturer websites (e.g. Apeel, Mori, Conservatis), consumer platforms (e.g. Stiftung Warentest), and innovation portals. Commercially available technologies are documented and categorized based on their preservation mechanisms (passive vs. active systems).

Table 1: Evaluation Matrix for Household Shelf-Life Technologies: Criteria, Scales, and Weightings

Criterion	Description	Evaluation scale (1–5)	Weighting (%)
Functional principle	Scientific validity, technical plausibility, and demonstrated consistency of the technology's mode of action	1 = no scientific basis 5 = basic functionality proven	25
Ease of use	The effort and knowledge required from users (e.g. inserting filters, cleaning, adjusting settings)	1 = very impractical 5 = very simple	10
Impact on Shelf-life in usage scenario	The measurable increase in the storage life of fruits and vegetables (e.g. number of days until spoilage becomes visible)	1 = hardly any effect 5 = strong effect	20
Hygiene & Food Safety	Does the product influence hygienic safety or microbiology? Does it contribute to actively improving microbiological safety (e.g. active germ reduction)?	1 = potentially risky 5 = hygienically safe	10
Cost/ Economic Efficiency	How is the impact on shelf-life compared with the costs (initial and ongoing costs, e.g. replacement parts, energy usage)?	1 = low 5 = high	10
Sustainability	Is the product reusable and environmentally friendly?	1 = disposable 5 = very sustainable	10
Availability	Is the product easily available to consumers?	1 = difficult to obtain 5 = widely available	5
Compatibility	The extent to which the technology is suitable for a wide variety of fruits and vegetables (universal vs. selective application)	1 = selective 5 = broad application range	10

To establish a scientific foundation for evaluation, the technologies are functionally categorized based on their operating mechanisms. Passive systems work by altering environmental conditions such as temperature, humidity, or gas exchange without triggering chemical or biological reactions.

In contrast, active systems engage directly with the food or its surrounding atmosphere through chemical, enzymatic, or biological processes. This classification allows for a more nuanced understanding of preservation potential and informs the subsequent assessment.

Based on this foundation, a multi-criteria evaluation matrix was developed to assess each solution in terms of functionality, usability, hygiene, sustainability, cost-efficiency, availability, and compatibility with household routines (Table 1).

Each criterion is rated on a 1–5 scale and weighted according to its relevance. The resulting scores are used to calculate a final performance score for each product.

To facilitate interpretation, a symbolic star rating system is applied:

- ☀️☀️☀️ = highly recommended (score ≥ 4.5)
- ☀️☀️ = recommendable (score 3.5 – 4.4)
- ☀️ = conditionally useful (score 2.5 – 3.4)
- ⚠️ = low consumer benefit (score < 2.5)

This scoring system enables the ranking of all evaluated innovations and the identification of the three most promising technologies for household use. The classification and evaluation framework are applied consistently across all product types to ensure comparability and transparency.

Results: Analysis of Household Shelf-Life Technologies

Technological Principles and Functional Classification of Preservation Methods

To structure the results, the technologies are first classified according to their functional principles (Table 2). This functional classification provides a scientific framework for evaluating their effectiveness and integration potential.

Table 2: Functional Classification of Household Shelf-Life Technologies by Mechanism and Application

Technology Type	Product Offering	Technological Background	Mechanism of Action	Reference
Passive Technologies				
Packaging Solutions	Reusable airtight containers, wraps	Barrier materials reduce gas exchange and moisture loss	Limits oxygen diffusion and water evaporation; slows microbial growth	Robertson 2016; Han 2014
Air Circulation	Ventilated storage systems	Structured airflow reduces localized humidity and ethylene	Enhances ventilation; prevents condensation and mould	Kader 2002
Temperature Control	Refrigeration and freezing	Lower temperatures reduce enzymatic and microbial activity	Slows respiration, ripening, and microbial proliferation	James & James 2010
Humidity Regulation	Moisture-absorbing pads	Hygroscopic materials stabilize humidity in enclosed spaces	Absorbs excess moisture; reduces microbial risk	Mahajan et al. 2008
Adsorption Filters	Activated carbon-based inserts	Physical adsorption of volatile compounds (e.g., ethylene)	Binds gases through surface interaction; no chemical transformation	Watkins 2006
Air Purification	Multi-stage filtration systems	Combination of particulate and gas-phase filtration	Removes airborne microbes and gases; improves hygiene	Gorris & Peppelenbos 1992
Active Technologies				
Edible Coatings	Lipid- or protein-based surface films	Biopolymer layers form semi-permeable barriers on produce surfaces	Reduces gas exchange and water loss; delays ripening and spoilage	Baldwin 1994; McHugh & Senesi 2000
Ethylene Absorbers	Reactive sachets or stickers	Oxidative or catalytic degradation of ethylene	Chemically neutralizes ethylene to delay ripening	Saltveit 1999; Wills & Golding 2016
Ozone-Based Systems	Low-dose ozone generators	Controlled release of ozone gas for disinfection	Oxidizes microbial cells and ethylene; reduces spoilage	Tzortzakis 2009
Gas-Releasing Disinfectants	Chemical gas-phase sanitizers	Controlled chemical reaction releases antimicrobial gases	Inactivates airborne and surface microbes; extends shelf life	Kim et al. 1999

Market Availability and Consumer Access

To complement the functional classification, Table 3 provides a structured overview of the current market landscape for preservation technologies in Germany. This analysis examines which of the classified technologies are commercially available, how they are positioned and marketed, their price range, and under what conditions they are accessible to consumers, thereby bridging the gap between theoretical potential and practical implementation.

Table 3: Market Overview of Shelf-Life Technologies

Product Type	Example Products / Brands	Claims	Price Range	Reference
Passive technologies				
Reusable Containers	Tupperware, Lock&Lock, IKEA 365+	Airtight, reusable, dishwasher-safe	€ 5–30	amazon 2025a, Freitag-Ziegler 2025
Silicone Food Lids	Food Huggers, IKEA ÖVERMÄTT	Stretchable, reduces drying out	€ 7–20	IKEA 2025
Beeswax Wraps	Bee's Wrap, PlastikfreieZone	Breathable, reusable, plastic-free	€ 7–25	Schulze et al. 2022
Freshness Bags	Profissimo Frischhaltebeutel	Moisture-resistant, keeps produce fresh longer	€ 0.75 (150 pcs)	Dm 2025, lioleli 2023
Refrigerator Drawers	Liebherr BioFresh, Bosch VitaFresh	Humidity-controlled compartments for fruits and vegetables	€ 500–2000	Kader 2013
Sponge Pad Filters	WIIYENA, Fridge Fresh	Moisture regulation, anti-mold, washable	€ 10–15	WIIYENA 2025
Active technologies				
Ethylene Absorbers	StixFresh, Conservatis, Vidre+	Slows ripening, extends shelf life by up to 14 days	€ 10–30	Ryp Labs 2023, Conservatis 2025, JANSSEN PMP 2022, Freshinset 2025
Air Purification Filters	Shelfy Luftfilter, OXO GreenSaver, Durafresh	Removes ethylene, bacteria, odours	€ 15–150	Saltveit 1998, Haus-HobbyGarten 2025, amazon 2025b
Ozone Generators	Klarstein, Ecozone, Ozonizer	Disinfects air, reduces spoilage, neutralizes odours	€ 30–100	Kaufland 2025, Tiwari & Muthukumarappan 2012
Gas-Based Disinfectants	Knick'n'Clean	Antibacterial gas-phase treatment for refrigerators	€ 30–50	Knick'n'Clean 2016
Edible Coatings	Apeel, Mori	Reduces moisture loss and oxidation, extends shelf-life pre-retail, B2B solution	–	Apeel Science 2024, Mori Silk 2025

Evaluation of Consumer-Relevant Preservation Technologies

To complement the functional and market classifications (Tables 2 and 3), Table 4 presents a multi-criteria evaluation matrix that integrates technological plausibility and market relevance. This structured assessment considers factors such as ease of use, shelf-life impact, hygiene and safety, cost-efficiency, sustainability, availability, and compatibility, allowing for a holistic evaluation of each technology's practical value in everyday household use.

Table 4: Evaluation of Consumer-Relevant Preservation Technologies

Product	Func-tional principle	Ease of use	Shelf-life	Hygiene & Safety	Cost/ Economic Efficiency	Sustain-ability	Avail-ability	Compati-bility	Overall Score	Overall rating
Passive technologies										
Reusable Containers	4	5	2	2	5	5	5	5	3,9	☀ ☀
Silicone Storage Bags	3	5	2	2	4	4	5	4	3,3	☀
Produce Nets	2	5	1	1	4	5	5	3	2,8	☀
Beeswax Wraps	3	5	2	1	5	5	5	3	3,3	☀
Silicone Food Lids	4	5	2	2	5	5	5	3	3,7	☀ ☀
Refrigera-tion	5	5	5	3	3	3	5	5	4,5	☀ ☀ ☀
Sponge pad filter	4	5	2	1	5	5	4	5	3,7	☀ ☀
Durafresh filter	2	4	2	1	2	3	4	5	2,6	☀
Active technologies										
Ethylene Absorber	2	4	3	1	2	3	4	5	2,8	☀
Air Purifi-cation Fil-ter	4	5	5	5	3	5	4	5	4,5	☀ ☀ ☀
Ozone Generator	2	4	3	5	3	5	5	5	3,6	☀ ☀
Gas-Based Disinfect-ant	4	5	3	5	2	3	4	5	3,8	☀ ☀
Edible Coatings (B2B)	4	5	3	3	3	5	1	1	3,1	☀

The evaluation reveals that passive systems such as refrigerators, freezers, reusable containers, and humidity-regulating pads consistently achieve high scores across all criteria, particularly due to their proven effectiveness, ease of integration, and widespread consumer familiarity. Refrigerators and freezers stand out as the most effective technologies overall (Kader 2013, Dincer & Kanoglu 2017).

Simpler tools like silicone lids, beeswax wraps, and produce nets also perform well in terms of usability and sustainability, although their direct impact on shelf life is limited (Schulze et al. 2022).

Among active systems, air purification filters and gas-based disinfectants achieved the highest overall ratings. Air filters effectively reduce ethylene, microbes, and odours, in enclosed environments (Ebrahimi et al. 2021, Chauhan & Jindal 2020).

Gas-based disinfectants lower microbial contamination through the controlled release of antimicrobial agents (Lisboa et al. 2024, Dubey et al. 2022). Both technologies show strong functional potential and are compatible with existing household appliances.

Discussion: Interpretation and Implications of Findings

Technological Principles and Functional Classification of Preservation Methods

Preservation technologies for fresh produce in domestic settings can be systematically categorized based on their underlying mechanisms and modes of interaction with food and its environment.

At the core of this framework lies the distinction between passive and active systems. Passive technologies include conventional packaging solutions, ventilated storage systems, temperature control appliances, and adsorption filters. Due to their simplicity and ease of integration, passive systems dominate the consumer market and are widely adopted in everyday household routines.

In contrast, active technologies involve mechanisms such as oxidative degradation, antimicrobial activity, and gas-phase interactions, as demonstrated by examples like edible coatings, ethylene absorbers, and ozone-based disinfection systems. While often more complex in application, active systems offer targeted preservation effects and are particularly effective in addressing specific spoilage factors such as microbial contamination or accelerated ripening.

The comparative analysis reveals that **temperature control** remains the most universally effective method across all produce types. However, its performance can be enhanced when combined with complementary technologies—particularly those that address humidity regulation, ethylene management, or microbial load. This synergy underscores the potential of **hybrid approaches**, which integrate passive and active mechanisms to achieve more robust and sustained shelf-life extension (Kader 2003, Dincer & Kanoglu 2017, Miller et al. 2013, Pandiselvam et al. 2022).

Among active technologies, **edible coatings** demonstrate strong potential in reducing moisture loss and oxygen exposure, although their current availability is largely restricted to B2B applications. Similarly, **ozone generators** and **gas-based disinfectants** exhibit pronounced antimicrobial effects but require careful handling due to safety considerations.

Overall, the classification highlights that **hybrid systems** - those combining environmental control with biochemical interaction - represent the most promising avenue for reducing food waste in private households. Their success, however, hinges on correct application, user education, and seamless integration into existing storage routines.

Market Availability and Consumer Access

Passive technologies - including reusable containers, silicone lids, beeswax wraps, and humidity-regulating pads - are widely distributed through B2C channels such as supermarkets, online platforms, and household goods retailers. These products are typically marketed for their ease of use, affordability, and environmental benefits, and they require minimal behavioral adaptation. Their broad availability and low entry cost contribute to high consumer acceptance and routine integration into household storage practices (Petersen et al. 2023).

More advanced passive systems, such as humidity-controlled refrigerator drawers or sponge-based filters, are integrated into added-value and premium appliance models. While they offer long-term benefits in terms of storage optimization and moisture regulation, their adoption is limited by higher acquisition costs.

Active preservation technologies, by contrast, show a more fragmented market presence. Some, such as ethylene absorbers (e.g. StixFresh, Conservatis), are available in consumer-friendly formats and can be purchased online. These products offer targeted preservation effects and are designed for easy integration into existing storage routines. However, other active systems - such as edible coatings (e.g. Apeel, Mori) and ethylene-blocking packaging inserts (e.g. Vidre+) - are primarily distributed via B2B channels and are not directly accessible to end users. Their impact on shelf life occurs upstream in the supply chain, prior to retail distribution.

Additional active systems, including ozone generators and gas-phase disinfectants (e.g. Knick’n’Clean), are marketed for their antimicrobial and air-purifying properties. These technologies offer added value in terms of hygiene and spoilage prevention but require careful handling and consumer education. Their adoption is further constrained by safety concerns, regulatory considerations, and relatively high price points (Sen 2022).

Overall, the market reflects a dual dynamic: passive technologies dominate in terms of accessibility, affordability, and consumer familiarity, while active systems - particularly those with scientifically validated mechanisms - are gaining relevance in niche applications. The most promising innovations combine functional effectiveness with ease of use and compatibility with household routines.

However, the broader integration of technical or industrial-grade solutions into the consumer market remains a challenge, particularly in terms of awareness, affordability, and trust (Petersen et al. 2023).

Evaluation of Consumer-Relevant Preservation Technologies

While the evaluation matrix identifies several high-performing technologies, the practical relevance of some solutions requires a more critical perspective. The leading performance of refrigerators and freezers is expected, given their long-standing role in food preservation and well-documented mechanisms for reducing enzymatic activity and microbial growth. Their universal availability and ease of use reinforce their continued relevance in household settings.

Simpler passive tools like beeswax wraps or produce nets, although not impactful in extending shelf life directly, contribute indirectly by regulating moisture and airflow. Their strengths lie in sustainability and usability, which support their adoption for specific use cases.

Active preservation systems, particularly air purification filters and gas-phase disinfectants, demonstrate considerable functional promise. Filters that incorporate HEPA or activated carbon stages effectively remove spoilage-related compounds, enhancing hygiene and freshness retention. Their integration into refrigerators is relatively straightforward, and current research supports their efficacy in controlled settings. Similarly, gas-based disinfectants offer a proactive method of reducing microbial load and are easy to implement with existing appliances.

However, despite their strong technical performance, several active systems raise questions regarding safety, long-term usability, and market readiness. Concerns about chemical residues from gas-phase disinfectants, for instance, highlight the need for more rigorous safety assessments. Likewise, while technologies like ethylene absorbers or edible coatings show functional promise, they lack sufficient validation in real-world household contexts or are not yet broadly accessible to consumers. This mismatch between laboratory potential and practical application may lead to inflated evaluation scores that do not fully reflect real-life effectiveness.

Future research should therefore prioritize long-term usability studies, independent field data, and consumer safety evaluations to ensure that guidance for household use is grounded in robust and realistic evidence. Bridging the gap between technical feasibility and consumer adoption remains essential for successful implementation.

Taken together, the findings highlight the practical relevance of combining passive and active preservation strategies in household settings. While passive systems are widely adopted due to their simplicity, active technologies offer targeted benefits that require further validation and user guidance. Their successful integration depends on usability, safety, and consumer trust—key factors for translating technical potential into everyday impact.

Conclusion

This study provides a comprehensive and evidence-based assessment of household technologies designed to extend the shelf life of fresh fruits and vegetables. By combining a functional classification with a structured market analysis and a multi-criteria evaluation matrix, the paper identifies both established and emerging solutions that are relevant for everyday consumer use.

The findings confirm that **passive technologies**, particularly refrigeration and freezing, remain the most effective and universally applicable methods. However, **active systems** - such as air purification filters and gas-based disinfectants—demonstrate significant potential when used in combination with temperature control. These hybrid approaches offer multifactorial benefits, including microbial reduction, ethylene management, and improved hygiene, and are especially promising for future household integration.

Despite their potential, many innovative technologies still lack independent validation and long-term field data. This limits consumer trust and hinders widespread adoption. Moreover, several high-performing solutions—such as edible coatings—are currently restricted to B2B applications, highlighting a gap between technological innovation and consumer accessibility.

To bridge this gap and unlock the full potential of freshness-preserving technologies, future research should focus on:

- Independent, long-term validation studies under real-life household conditions.
- Consumer-cantered design to improve usability, affordability, and trust.
- Interdisciplinary collaboration between food scientists, appliance manufacturers, and behavioural researchers.
- Policy and regulatory frameworks that support safe and transparent innovation transfer from B2B to B2C markets.

Ultimately, reducing food waste at the household level requires not only technological innovation but also systemic change—combining smart tools, informed consumers, and supportive infrastructure. This study lays the groundwork for such an integrated approach and calls for continued research and development to ensure that the most effective, safe, and sustainable solutions reach the people who need them most.

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