Meat Packaging: A Determinant of Product Quality and Shelf Life

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Abstract
Packaging technologies play a central role in preserving meat quality, ensuring food safety, and promoting sustainability in the food industry. As consumer preferences increasingly favor minimally processed, high-quality, and eco-friendly products, packaging has evolved beyond its traditional role of containment and protection. Modern solutions such as modified atmosphere packaging (MAP), vacuum sealing, and biotechnology-based active and intelligent systems contribute significantly to extending shelf life and maintaining the physicochemical and microbiological stability of meat products throughout distribution and storage. This paper explores the intersection of biotechnology and packaging innovation, with a focus on sustainable materials and smart technologies that respond to both product conditions and environmental requirements. The use of biodegradable materials, sensors, and antimicrobial components is gaining traction as a way to meet sustainability goals while ensuring food safety and reducing waste. The integration of biotechnological advances into packaging systems has the potential to reshape meat preservation strategies, making them more efficient, transparent, and environmentally responsible.

Keywords: meat packaging, food safety, biotechnology, modified atmosphere packaging (MAP), food waste, active packaging

1. Introduction

Food packaging is essential for shielding products from environmental influences while ensuring their preservation in an economical and sustainable way. By ensuring food safety and reducing environmental impact, packaging meets the needs of both the food industry and consumers. Recent developments in packaging technology have resulted in the emergence of active and intelligent packaging systems. Active packaging, in particular, is an innovative technology designed to extend the shelf life of perishable goods and enhance their quality and safety through direct interaction with the product. This approach also reduces the need to incorporate active compounds directly into the food, limits substance migration from the packaging to the product, and can eliminate certain industrial processes that may introduce pathogens [1]. Consequently, it contributes to lowering the risk of foodborne illnesses and reducing the occurrence of product recalls [2].

Given the persistent challenges of food spoilage and contamination, such innovations are increasingly important. A commonly employed method for inhibiting pathogenic microorganisms involves applying antimicrobial compounds to food surfaces. However, the efficacy of this method is often limited due to interactions between the compounds and the food matrix, which can hinder their activity and practical use [3].

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Beyond microbial safety, packaging serves a broader role in preserving food quality throughout the stages of transportation, distribution, and storage [4]. Despite ongoing advancements, substantial amounts of edible food continue to be wasted throughout the supply chain. In Europe, food waste is estimated at around 89 million tons per year, with notable differences across countries and sectors [5]. Effective packaging helps address this issue by providing a barrier against chemical, biological, physical, mechanical, and environmental stressors that can negatively impact nutritional content, sensory attributes, and product longevity [6].

To further combat food waste, various packaging optimization strategies have been proposed. These include offering a wider range of portion sizes tailored to consumer needs and designing packaging systems that better preserve freshness and delay spoilage [5].

2. Materials and methods

The data and information presented in this work were obtained through an extensive literature review conducted using reputable scientific databases, including ScienceDirect, Google Scholar, PubMed, and Scopus. The objective of the research was to identify the most recent and relevant studies related to modern meat packaging technologies and their influence on shelf life extension, food safety, and sustainability.

To retrieve specific and targeted information, key search terms were used, such as: “meat packaging”, “modified atmosphere packaging (MAP)”, “vacuum packaging”, “active packaging”, “smart packaging”, “biodegradable packaging”, “shelf life extension”, “food safety”, “food waste reduction”, and “sustainable food packaging”.

The literature selection was limited to scientific articles published between 1993 and 2024, written in English, in peer-reviewed journals with impact factor. Preference was given to studies that presented experimental results or systematic reviews focusing on packaging methods applied to meat and other perishable food products.

The analysis was conducted using a narrative and thematic approach, synthesizing information on: the operating principles of MAP and vacuum packaging; active and intelligent packaging; the use of biodegradable and edible materials; and their contribution to food loss reduction and environmental protection.

The ultimate goal was to outline current trends in meat packaging and emphasize the importance of implementing sustainable and efficient solutions within the modern food supply chain.

3. Results and discussion

Food safety and product preservation have always been topics of major interest in scientific research, playing a important role in human nutrition [7].

Meat is a important source of high-quality dietary protein for a significant portion of the global population. However, its consumption remains a contentious issue worldwide, primarily due to concerns regarding its impact on human health, the environment, and animal welfare [8].

The overall quality of meat, as with any food product, is influenced not only by its source but also by the methods of processing, whether industrial or domestic [9].

Meat spoilage is a complex process driven by various biological, chemical, and physical factors, all of which can significantly compromise its quality. In addition to microbial spoilage, lipid and protein oxidation are key factors contributing to the functional, sensory, and nutritional deterioration of meat and meat products. Lipid oxidation, in particular, can lead to the development of off-flavors and odors, changes in color and texture, and the potential formation of harmful compounds [10].

Given the susceptibility of meat to spoilage, packaging plays a important role in maintaining its freshness, safety, and quality, offering an effective solution to the challenges associated with deterioration.

Modern Packaging Technologies and the Role of Biotechnology

Food packaging has evolved beyond its original function of protecting the product, now serving multiple roles in relation to the packaged product [11]. Packaging characteristics directly impact consumer purchase intentions and decisions [12-13]. Factors such as appearance, water retention capacity, color, microbial quality, lipid stability, nutritional value, and palatability (texture, taste, and other sensory properties) are key determinants of quality perception [14-16]. The functions of packaging can be divided into four primary roles: protection, preservation, ease of handling, and communication [17].

In recent years, packaging technologies have advanced considerably, including methods such as modified atmosphere packaging (MAP), vacuum packaging, and the advancement of active and intelligent packaging systems. These modern approaches not only enhance the efficiency of food preservation but are increasingly supported by advancements in biotechnology, which help optimize functional properties and contribute to the sustainability of the food supply chain.

Modified Atmosphere Packaging (MAP)

Modified Atmosphere Packaging (MAP) has been utilized in the food industry for over 90 years to extend shelf life and preserve the quality and safety of fresh and freshly processed food products. In recent years, MAP has undergone rapid advancements in both scientific research and industrial applications, and it is now considered one of the most efficient and versatile technologies for packaging fresh and fresh-cut products [18].

This method involves replacing the natural atmosphere within the packaging with a mixture of gases, rather than using a single gas, and can be applied using bags, foil trays, or packaging films. Oxygen (O_2) promotes the formation of red oxymyoglobin pigments, which oxidize over time, leading to color changes. Nitrogen (N_2), an inert gas, fills the packaging and prevents it from collapsing during the vacuum-sealing process. Carbon dioxide (CO_2) is used to inhibit the growth of microorganisms. Carbon monoxide (CO) also creates a red pigment, carboxymyoglobin, which remains much more stable than oxymyoglobin, helping to maintain the red color of meat for a longer period. The combination of various gases, adjusted to optimal concentrations, creates an ideal environment for preserving the desired characteristics of meat products [19].

MAP not only extends shelf life but also enhances the quality and safety of packaged food.

Table 1. Applications of MAP

Food Category	Objective	Key information	Recommended gas mixtures/conditions
Red Meat and Poultry	Maintain myoglobin in red meat, prevent aerobic spoilage bacteria, preserve color, and extend the shelf life of meat.	- Myoglobin in red meat, when bound to oxygen, forms oxymyoglobin, maintaining the "supermarket red color." - Pseudomonas species are the primary aerobic spoilage bacteria in red meat, and their growth is inhibited by CO_2 [20]. - Poultry meat color is less significant, as it is classified as white meat [21]. - The exclusion of oxygen is recommended in poultry MAP systems [22].	- For red meat: 20-30% CO_2 and 70-80% O_2 to inhibit aerobic spoilage bacteria and maintain color [20]. - The recommended gas-to-product ratio is 2:1. For minced meat and roasts: 0.5% CO in MAP for red color stability [23]. - For poultry: Exclusion of oxygen is recommended to ensure color stability [22].
Fish and Other Sea Products	Extend shelf life, preserve natural appearance, prevent oxidation, and inhibit the growth of anaerobic bacteria.	- The higher lipid content in fish makes oxidation a more significant deterioration process compared to red meat [23]. - Fish contains lower levels of myoglobin, making oxidation less relevant. - CO_2 helps prevent oxidation and extend shelf life; however, high levels can promote the growth of anaerobic bacteria, such as *Clostridium botulinum* [24]. - N_2 helps prevent packaging collapse [24].	- For black fish: 30% O_2, 40% CO_2, and 30% N_2 for white (non-fat) fish [25]. - An oxygen-free atmosphere may pose risks for the development of anaerobic bacteria [24]. - The use of antioxidants to prevent oxidation in MAP [24].

Vacuum packaging (VP)

Vacuum packaging (VP) refers to meat that is placed in a low oxygen permeability bag, followed by the application of vacuum before sealing [26]. As the vacuum is applied, the packaging collapses around the product, ensuring close contact between the film and the meat. This contact can be further enhanced through the use of heat-shrink wrapping. Alternatively, vacuum packaging can be applied to retail-sized cuts by thermoforming a "skin" around the meat. This process is accomplished by creating a deep vacuum on both sides of the heated packaging film, followed by venting the top side to air, which causes the film to tightly conform to the product and eliminate any air gaps around it (though not within the meat itself).

When meat is sealed in oxygen-impermeable materials with minimal headspace, the residual oxygen at the meat/package interface is quickly converted into carbon dioxide as a result of the meat's own respiratory activity [27]. In low-oxygen atmospheres, the growth of aerobic spoilage bacteria is suppressed, leading to a shift in the microbial population toward slow-growing, CO_2-tolerant bacteria [28].

To highlight the effects of vacuum packaging on the microflora of refrigerated meat, Aura Darabă (2003) conducted an experimental study at the "Dunărea de Jos" University of Galați. The research focused on changes in the non-specific microbiota of pork samples (musculus *Longissimus dorsi*) stored under refrigerated conditions (0–4 °C) for a period of eight days. The results showed a significant reduction in aerobic mesophilic and psychrotrophic bacteria, alongside a slight increase in lactic acid bacteria and facultative anaerobes, supporting the effectiveness of vacuum packaging in delaying microbial spoilage [29].

Table 2. Evolution of microbial groups during vacuum storage (0–8 days, 0–4°C)

Storage time (days)	Aerobic mesophilic bacteria (log_{10} CFU/g)		Psychrophilic and facultatively psychrophilic bacteria, log_{10} CFU/g		Lactic acid bacteria, log_{10} CFU/g		Enterobacteria, log_{10} CFU/g		Anaerobes, log_{10} CFU/g	
	1	2	1	2	1	2	1	2	1	2
0	3.53	3.53	3.00	3.00	3.47	3.47	-	-	-	-
2	4.00	3.59	3.90	3.24	3.80	3.60	2.90	-	2.00	-
4	4.80	3.69	5.30	4.46	3.60	3.90	4.40	1.20	2.95	2.47
6	5.60	4.20	6.70	4.55	4.00	4.20	5.90	1.30	4.90	2.50
8	7.20	4.72	8.40	4.74	4.10	4.80	7.20	1.40	6.17	2.70

"1" = Aerobic; "2" = Anaerobic; "-" = Below detection limit.

The values in the table represent the average concentrations of the main microbial groups, expressed as base-10 logarithms of colony-forming units per gram (log CFU/g), measured at regular intervals during the storage of vacuum-packaged refrigerated meat at a constant temperature of 0–4°C.

Active and Intelligent Packaging Based on Biotechnology

Active packaging refers to a system where the packaging is altered to preserve or improve the sensory, safety, and quality attributes of food. In contrast, intelligent packaging is characterized by the use of an internal or external indicator to track and provide information on the food's history, quality, and safety [30].

These technologies are already being applied in sectors like meat, dairy, and bakery packaging, where they help extend the freshness and safety of food for longer periods. Additionally, smart packaging adds an extra layer of protection by offering consumers real-time information about the product's condition.

Sustainable Packaging and Reducing Environmental Impact

The packaging industry plays a key role in reducing environmental impact and promoting sustainability. With the growing awareness of environmental issues, research and innovation in packaging has led to the development of more eco-friendly solutions. Among the most important areas of focus are the use of biopolymers and biodegradable materials, the implementation of effective strategies to reduce food waste, and the adoption of environmental regulations aimed at reducing pollution and waste.

Biopolymers offer a promising alternative to conventional plastics with low environmental impact. They are derived from natural sources such as starch, cellulose, chitosan or polylactic acid (PLA) and are biodegradable, thus reducing the accumulation of plastic [39].

Another notable innovation in biodegradable packaging is edible films and coatings. These materials, made from proteins, polysaccharides, or lipids, offer both mechanical protection and barriers against moisture and gases, ensuring the safety and quality of food products [35].

Table 3. Classification and Functions of Active Packaging for Food Products

Packaging type active	Features / principle of operation	Main functions	Examples	References
Active Non-Migratory Packaging	Does not release substances into the product; instead, it influences the internal atmosphere through absorption or scavenging.	- Removal of oxygen, ethylene, and moisture. - Slows down oxidation and microbial spoilage. - Extends freshness.	- Oxygen absorbers. - Desiccants (moisture). - Ethylene filters.	[31- 34]
Active Release Packaging	Enables controlled migration of active ingredients (AI) into the environment or food. Mechanisms include release, buffering, and blocking.	- Release of antimicrobial agents. - Release of antioxidants. - Regulation of atmospheric conditions (e.g., CO_2). - Enhancement of nutritional value and safety.	- CO_2 emitters. - Antimicrobial packaging (e.g., based on nisin). - Antioxidant packaging.	[32, 33, 35, 36]
Extended Functions in Packaging	Serves as a protective barrier while actively interacting with the food. This includes functions such as blocking, absorbing, buffering, or releasing active ingredients (AI).	- Protection against biochemical, microbial, and oxidative alterations. - Delay of respiration rates. - Reduction of moisture migration. - Improvement of food safety and quality.	- Edible films with active ingredients (AI). - Buffering packaging. - Packaging with essential natural oils.	[33, 34, 37]
Sustainable Technologies	Biodegradable, edible films and coatings made from natural sources, supporting sustainability objectives.	- Minimization of food waste. - Preservation of food value. - Environmentally sustainable packaging.	- Films based on alginates, pectin, chitosan. - Active coatings with natural antioxidants and antimicrobials.	[11,38]

Moreover, edible films and coatings can provide various additional features that enhance both the quality and sustainability of food. For instance, they offer protection against UV light, which helps prevent the degradation of light-sensitive foods [40]. These active packaging solutions are capable of transporting dissolved substances, such as salts, additives, pigments, as well as water vapor, organic compounds (like flavors and solvents), and gases (e.g., oxygen, carbon dioxide, nitrogen, and ethylene), thereby regulating the exchange of substances between food and its environment [40, 41].

Furthermore, edible films effectively protect food from mechanical damage, such as impacts or cuts, thereby preserving the physical integrity of products [42]. Another significant benefit is the extension of shelf life, achieved by delaying oxidation and spoilage processes [41]. Edible films can also incorporate bioactive substances like antioxidants, which help maintain food quality [43, 44]. Additionally, antimicrobial effects are often incorporated into these films, using materials such as silver nanoparticles to prevent bacterial and mold growth, which can further reduce contamination risks [43, 44]. Some films even include beneficial microorganisms, such as probiotics, which offer additional health benefits to consumers.

All these advantages stem from the use of biodegradable materials, which not only reduce the environmental impact of packaging but also contribute to food preservation and waste reduction. [42]. Sustainable packaging, therefore, plays a important role in combating food waste by providing superior protection and ensuring that food stays in optimal conditions throughout the supply chain.

The Need to Reduce Food Waste

Food waste is a major global issue with significant economic, ethical, and environmental implications. Innovative packaging plays an essential role in addressing this challenge through methods such as modified atmosphere packaging (MAP), the use of smart sensors, and active materials, all aimed at preserving the freshness and safety of food products [45].

The consequences of food waste go beyond economic and ethical concerns, directly impacting the sustainability of the food supply chain. Food waste (FW) can occur at every stage of the agri-food chain—from raw material production to food processing, storage, marketing, distribution, and ultimately, consumption [46].

Table 4 presents key data on the scale of food waste in the European Union, the associated economic costs, the critical points in the food chain where the greatest losses occur, and case studies from the retail sector.

Table 4. Estimates and Drivers of Food Waste in the EU

Category	Details	Sources
Total food waste in the EU	Between 88 and 129 million tonnes per year	[46-48]
Economic cost of food waste	Estimated at €143 billion per year	[46-48]
Stages of the food supply chain affected	- Primary production (inefficient harvesting, strict aesthetic standards) - Processing and manufacturing (losses during packaging and cleaning) - Storage and transportation (spoilage due to inadequate conditions) - Retail and distribution (product expiration, poor handling) - Final consumption (oversized portions, food discarded by households and restaurants)	[46]
Retail food waste (2012)	4.6 million tonnes of food wasted in retail	[48]
Retail and distribution food waste (2011)	6.7 million tonnes of food wasted in these sectors	[46]
Key factors contributing to retail food waste	- Expired shelf life - Transport and handling damage - Aesthetic requirements for products	[49]
Case study: store in Italy	A single retail location wasted 70.6 tonnes of food in one year, resulting in a loss of €170,000	[50]
Highest waste stages in industrialized countries	Retail, catering industry, and final consumers	[51]
Impact of food waste	Significant economic and environmental impact, especially in the final stages of the food chain	[52]

One of the most effective strategies for addressing food waste is the development and implementation of innovative packaging solutions. Smart packaging technologies, including modified atmosphere packaging (MAP), intelligent sensors, and active materials, play an important role in extending product shelf life, minimizing spoilage, and reducing overall food loss. These technologies enable real-time monitoring of storage and transportation conditions, helping to ensure that food quality is preserved throughout the supply chain, right up to the point of consumption.

In addition, the adoption of biodegradable and reusable packaging materials significantly contributes to lowering the environmental impact linked to food waste.

Effectively tackling food waste requires the integration of both innovative and sustainable approaches, aimed at reducing not only economic losses but also the broader environmental consequences. Smart packaging and advanced technologies thus represent an essential step forward, supported by continuous advancements in scientific research and evolving regulatory frameworks.

4. Conclusions

The packaging of food — particularly meat and other perishable products — plays a key role in preserving quality, ensuring safety, and supporting sustainability across the entire supply chain. Modern technologies such as Modified Atmosphere Packaging (MAP), active and intelligent packaging, together the use of biopolymers and biodegradable materials, show significant potential in extending shelf life, preventing spoilage, and reducing microbial contaminationThrough the incorporation of antimicrobial agents, smart sensors, and functional edible films, packaging is transformed from a passive container into an active component in food preservation and consumer protection. At the same time, these innovative solutions play a important role in addressing food waste — one of the most pressing challenges of our time with significant economic, social, and environmental repercussions.

The adoption of sustainable and efficient packaging is not only a technological innovation, but a necessary step toward building a more responsible and resilient food system. Therefore, the ongoing development and implementation of these packaging solutions represent a strategic priority for the future of the food industry, aligned with global goals for sustainability and food safety.

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