PRESERVATION AND PACKAGING STRATEGIES FOR REFRIGERATED MEAT: EFFECTS ON QUALITY, SAFETY, AND SHELF-LIFE

M. Arsene[1*], G. V. Hoha[1], M. A. Davidescu[1], I. M. Balmuș[2], A. Ciobanu[1], R.-M. Radu-Rusu[1]

[1] *"Ion Ionescu de la Brad" Iasi University of Life Sciences, 3 Mihail Sadoveanu Alley, 700490 Iasi, Romania*
[2] *"Alexandru Ioan Cuza" University, Iasi, Bulevardul Carol I, Nr.11, 700506, Romania*

Abstract

The preservation of refrigerated meat remains a major challenge due to the combined effects of microbial growth, lipid oxidation, and sensory deterioration during storage. In this context, the aim of the present review is to analyze the main preservation and packaging technologies currently applied to refrigerated meat, with emphasis on their effects on food safety, physicochemical stability, shelf-life, and consumer-oriented quality attributes. The paper synthesizes recent literature on conventional packaging systems, particularly vacuum packaging and modified atmosphere packaging, as well as on emerging active and intelligent packaging solutions. Special attention is given to the mechanisms through which these systems influence oxidative processes, microbial development, color stability, texture, and freshness monitoring along the cold chain. The reviewed studies indicate that vacuum packaging and modified atmosphere packaging remain the most widely used strategies, while active packaging based on antioxidants, antimicrobials, and oxygen scavengers, together with intelligent systems using freshness indicators and sensors, represent promising directions for further improvement. The available literature supports the idea that the preservation of refrigerated meat increasingly relies on multifunctional packaging approaches capable of improving product stability, supporting quality monitoring, responding to current industrial and market requirements and avoiding food waste.

Key words: *refrigerated meat, food waste, active and intelligent packaging, shelf-life, food safety*

1. INTRODUCTION

The preservation of refrigerated meat represents a complex and multidimensional challenge, governed by the interaction between microbial dynamics, physicochemical transformations, and continuously evolving consumer expectations. Although refrigeration remains the fundamental method for slowing biochemical reactions and microbial proliferation, its limitations are well documented, particularly in the context of psychrotrophic microorganisms capable of growing at temperatures between 0 and 4°C [1], [2]. Consequently, quality deterioration continues during storage, affecting both safety and sensory attributes.

In response to these limitations, packaging technologies have become essential tools for extending shelf-life and maintaining product stability. Conventional systems such as vacuum packaging (VP) and modified atmosphere packaging (MAP) operate primarily by controlling oxygen availability and gas composition. In VP systems, the near-complete removal of oxygen reduces oxidative reactions and inhibits aerobic microorganisms [3], while

* Corresponding author: maria.arsene@iuls.ro
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MAP enables tailored gaseous environments to balance microbial inhibition and oxidative stability. These approaches align with current consumer preferences for minimally processed foods [4], yet require continuous optimization to reconcile safety requirements with desirable sensory characteristics.

The aim of the present study is to evaluate how packaging systems influence the quality and safety of refrigerated meat. The objectives include the analysis of conventional systems (vacuum packaging and modified atmosphere packaging) and modern technologies (active and intelligent packaging), the study of interactions between packaging and meat spoilage pathways, the synthesis of scientific literature regarding microbial, oxidative, and sensory effects, and the identification of gaps in the literature related to economic assessment and methodological variability.

To provide a comprehensive overview of the scientific landscape, a bibliometric keyword co-occurrence analysis was performed using *VOSviewer*. The resulting network (Figure 1) highlights several major thematic clusters, including packaging technologies, physicochemical stability, microbiological safety, and consumer-oriented quality attributes. This interconnected structure demonstrates that modern preservation strategies must be approached in an integrated manner, reflecting the complex interactions between packaging systems and meat quality determinants.

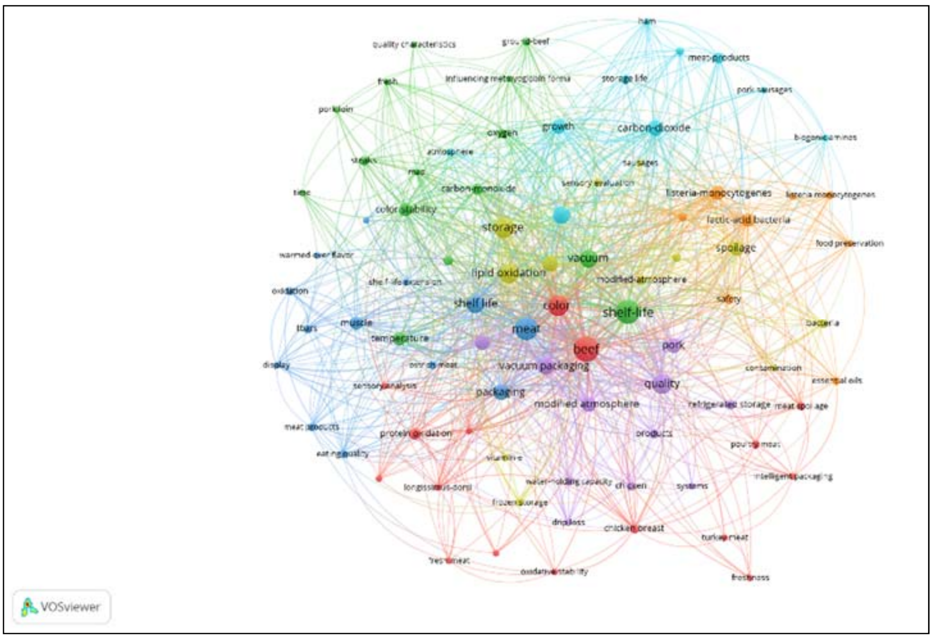

Fig. 1 Co-occurrence network of keywords related to refrigerated meat packaging based on Web of Science articles (VOSviewer visualisation). The node size represents the frequency of occurrence, while the proximity of the connecting lines reflects the strength of association between nodes. The colour coding corresponds to their respective thematic clusters. The overlapping in the figure does not affect its scientific understanding.

2. PACKAGING SYSTEMS, SPOILAGE MECHANISMS AND PRESERVATION DYNAMICS

The effectiveness of packaging technologies in refrigerated meat preservation is closely linked to their interaction with the primary pathways of deterioration, namely microbial growth and oxidative processes. Microbial spoilage is driven by the proliferation of psychrotrophic bacteria, such as *Pseudomonas spp.* and *Listeria monocytogenes*, which generate metabolites responsible for off-odors, slime formation, and structural degradation. In parallel, oxidative reactions affect both lipids and pigments, leading to rancidity and discoloration through the conversion of oxymyoglobin to metmyoglobin [20]. These processes occur simultaneously and ultimately define the shelf-life of the product.

The performance of preservation systems is further modulated by both intrinsic and extrinsic factors. Intrinsic properties, including water holding capacity, lipid composition, and myoglobin chemistry, determine susceptibility to oxidation, moisture loss, and color instability. For instance, variations in water retention influence drip loss and texture, while lipid composition affects oxidative stability. At the same time, extrinsic factors such as temperature, light exposure, relative humidity, and packaging atmosphere significantly influence microbial growth kinetics and reaction rates. Even slight deviations in temperature can accelerate microbial proliferation, while light exposure may intensify pigment oxidation, reducing visual appeal.

Within this framework, conventional packaging systems remain widely applied due to their effectiveness and adaptability. Vacuum packaging functions by eliminating oxygen, thereby inhibiting aerobic microorganisms and slowing lipid oxidation. However, it often results in a darker, purplish color due to deoxymyoglobin formation, which may reduce consumer acceptance. Modified atmosphere packaging utilizes controlled gas mixtures, typically involving CO_2, O_2, and N_2. Carbon dioxide exerts a bacteriostatic effect, oxygen contributes to color retention through oxymyoglobin stabilization, and nitrogen acts as an inert filler. Despite these advantages, MAP systems are highly dependent on precise gas composition, and elevated oxygen levels may accelerate oxidative degradation [5], [6].

Recent developments have introduced active packaging systems, which go beyond passive protection by directly interacting with the product environment. These systems incorporate oxygen scavengers, antimicrobial compounds, or natural antioxidants into packaging materials, allowing them to either absorb undesirable compounds or release protective substances during storage [7], [8], [9]. For example, gelatin–nanochitosan films enriched with essential oils have demonstrated the ability to inhibit pathogens such as *Listeria monocytogenes* while extending shelf-life under refrigeration conditions. Such systems offer dual functionality by simultaneously controlling microbial growth and oxidative processes.

Complementary to active systems, intelligent packaging technologies provide monitoring capabilities without directly altering the product (Table 1). These include time–temperature indicators, gas sensors, and freshness indicators capable of detecting changes in pH or volatile compounds associated with spoilage [10]. By enabling real-time assessment of product condition, intelligent packaging improves traceability and supports decision-making throughout the supply chain. However, widespread implementation is still limited by factors such as cost, sensor sensitivity, and environmental considerations [11].

An important aspect of modern research focuses on understanding microbial succession under different packaging conditions. Packaging atmospheres influence not only microbial load but also community structure and metabolic activity, which in turn affect spoilage progression and safety risks [12]. At the same time, the interaction between active compounds and sensory attributes remains insufficiently explored, particularly regarding their impact on flavor, texture, and consumer acceptance after cooking [13].

From a practical perspective, preservation efficiency depends on the interaction of multiple factors, including physicochemical stability, microbial control, and sensory quality. Lipid oxidation is strongly influenced by oxygen availability, while microbial stability depends on the inhibition of specific spoilage organisms. Sensory attributes, especially color, are closely linked to pigment chemistry and packaging atmosphere. Therefore, shelf-life extension is not solely a function of microbial suppression but also of maintaining acceptable sensory characteristics.

Table 1. Comparative overview of meat preservation methods, mechanisms of action, and main quality and safety limitations

Method	Mechanism	Effect on Quality/Safety	Limitations
Refrigeration	Low temp slows reactions	Reduces but does not halt microbial growth	Spoilage at 0–4 °C possible
VP	Oxygen removal	Inhibits aerobes; enhances oxidative stability	Potential discoloration; variable consumer acceptance
MAP	Modified gaseous mix (O_2, CO_2, N_2)	Extends shelf-life; maintains color; reduces oxidation	Gas mix must be optimized per product
AP	Active agents/scavengers in material	Targets microbes; controls oxidation/moisture	Limited knowledge on sensory changes
Intelligent Packaging	Sensors/indicators in pack	Monitors condition/alerts user; aids logistics	Technology cost; disposal/environmental concerns

**VP- Vacuum packaging, MAP – Modified atmosfere packaging, AP- active packaging*

Current trends indicate a shift toward integrated preservation systems that combine conventional and advanced technologies. The simultaneous use of VP or MAP with active and intelligent packaging elements offers the potential to optimize preservation outcomes by addressing multiple degradation pathways. In addition, the development of bio-based materials and nanotechnology-enhanced films aims to improve barrier properties while reducing environmental impact [11], [14].

Despite these advances, several gaps remain in the literature. Economic evaluations of advanced packaging systems at industrial scale are limited, and methodological variability, particularly in studies involving natural extracts, complicates result comparability. Furthermore, data on consumer acceptance and willingness to pay for innovative packaging solutions remain insufficient [15]. Research integrating multiple technologies, such as the combination of active packaging, intelligent systems, and additional treatments like UV, is also relatively scarce, highlighting an important direction for future investigation.

Future developments in refrigerated meat preservation are expected to focus on three main directions: the integration of active and intelligent functions into unified systems, the use of sustainable materials based on biopolymers and natural compounds, and the dynamic optimization of packaging atmospheres tailored to specific meat types. These approaches aim to extend shelf-life, enhance traceability, and reduce food waste across the supply chain.

The preservation of refrigerated meat relies on achieving a balance between microbiological stability and oxidative control, while maintaining sensory quality. The transition from conventional to advanced and integrated packaging systems represents a key step toward more efficient, sustainable, and consumer-oriented preservation strategies.

3.CONVENTIONAL PRESERVATION AND PACKAGING APPROACHES FOR REFRIGERATED MEAT

Conventional preservation strategies for refrigerated meat are primarily designed to control microbial growth, reduce oxidative deterioration, and maintain acceptable sensory properties through well-established industrial practices. Among these, refrigeration, freezing, salting, curing, drying, and thermal processing have traditionally been employed across the meat sector [27]. However, although such methods have demonstrated reliability over time, their applicability to fresh meat is increasingly constrained by consumer demand for minimally processed products and by the high susceptibility of fresh meat to quality loss during chilled storage.

Refrigeration remains the basic preservation approach for fresh meat. Storage at temperatures close to 0 °C slows enzymatic activity and microbial growth, but it does not completely suppress the metabolism of psychrotrophic microorganisms, which continue to proliferate, albeit at a reduced rate, during storage [10]. Consequently, refrigeration alone is insufficient to ensure long shelf-life or complete microbiological stability. Freezing, by contrast, markedly extends storage life by halting microbial growth at temperatures of −18°C or below. Nevertheless, the formation of ice crystals during freezing and thawing disrupts muscle structure, leading to purge loss, textural degradation, and reduced juiciness, which may compromise product quality when a fresh-like sensory profile is desired [10].

Within this conventional preservation framework, vacuum packaging (VP) represents an important development. By removing air from the package and sealing the product in low-permeability films, VP reduces oxygen availability and thereby limits oxygen-dependent spoilage pathways. This results in lower lipid oxidation rates and effective inhibition of aerobic microorganisms [3]. However, the reduced oxygen environment also promotes the formation of deoxymyoglobin, giving meat a purplish appearance that may be less attractive to consumers despite the absence of actual quality deterioration [28]. Evidence indicates that combining VP with oxygen scavengers can extend the safe storage period from approximately 10 to 14 days under chilled conditions, with minimal effects on pH or textural parameters when storage is maintained close to freezing temperatures [19].

Modified atmosphere packaging (MAP) follows the same preservation objective as VP but relies on replacing ambient air with controlled gas mixtures, commonly composed of O_2, CO_2, and N_2 [21]. The use of elevated oxygen concentrations can preserve the bright red color of fresh meat for longer periods by stabilizing oxymyoglobin, but this advantage is often offset by increased lipid peroxidation in the absence of sufficient antioxidant protection. In contrast, high-CO_2 atmospheres are particularly effective in suppressing aerobic microbial growth, although they may induce slight acidification, stimulate purge formation, and accelerate pigment instability if oxygen levels are too low to maintain color [29]. Furthermore, the permeability of the packaging material plays a decisive role, as gas composition may shift over time due to microbial metabolism, tissue respiration, and diffusion through the film.

Hermetic packaging systems without active functions also remain widely used because of their simplicity, relatively low cost, and compatibility with existing processing infrastructure. Their main preservative role lies in preventing recontamination from the surrounding environment; however, without oxygen control or gas modification, they provide only limited protection against oxidation or microbial activity in residual headspace oxygen. For this reason, they are generally effective only when combined with strict temperature control, protection from light, and short storage periods.

In some processing systems, antimicrobial sprays or dips-such as organic acid solutions-are applied before packaging to reduce initial surface contamination [27]. While these treatments may be useful in lowering microbial loads at the beginning of storage, their effectiveness is often short-lived because proteins and tissue components may neutralize their activity, while diffusion into deeper muscle layers remains limited. As a result, such interventions should be considered supportive rather than sufficient on their own.

Overall, the microbiological and physicochemical consequences of conventional refrigerated preservation methods differ substantially depending on the system used. Refrigeration alone provides only moderate shelf-life extension and limited oxidative protection. Freezing ensures microbiological stability but compromises texture after thawing. Vacuum packaging effectively suppresses aerobes and retards oxidation, yet introduces color-related marketability issues. High-O_2 MAP improves color retention but may accelerate oxidative damage, whereas high-CO_2 MAP more effectively suppresses spoilage microorganisms, though not without consequences for acidity and pigment stability. Therefore, the selection of a conventional preservation strategy depends not only on technical efficacy, but also on the intended distribution chain, shelf-life target, retail presentation requirements, and available cold-chain infrastructure.

From a practical standpoint, MAP is often more suitable for long-distance distribution and retail display, where color retention is critical, while VP is preferred in shorter supply chains or export routes where oxidative stability and simplicity of application are prioritized. Recent industry practice also shows a growing tendency to enhance conventional systems with functional elements, such as the incorporation of antioxidants like rosemary extracts into films used in otherwise traditional packaging systems [30]. These hybrid approaches suggest a transitional stage in which conventional technologies are being progressively refined rather than fully replaced, emphasizing the continued relevance of established packaging methods within modern refrigerated meat preservation.

Overwrap packaging

Among conventional packaging systems, overwrap packaging remains one of the most widely used formats for fresh meat display at retail level. In this system, meat cuts are placed on trays-commonly expanded polystyrene with absorbent pads-and covered with an oxygen-permeable transparent film such as polyvinyl chloride (PVC) [25]. The principal advantage of this format lies in its visual presentation, as oxygen diffusion from the surrounding environment promotes oxymyoglobin formation and thus maintains the bright red color strongly associated by consumers with freshness [20].

Despite this visual benefit, the continuous availability of atmospheric oxygen creates several important drawbacks. First, lipid oxidation is accelerated, resulting in rancid off-flavors, nutrient deterioration, and reduced sensory quality. Protein oxidation may also occur, negatively affecting water-holding capacity and palatability. Second, the aerobic environment favors the rapid development of spoilage microorganisms, especially psychrotrophic bacteria capable of growing under refrigerated conditions. Such microbial activity may generate undesirable sulfur-containing volatiles and unpleasant odors before overt visual spoilage is evident [24], [31].

Shelf-life under overwrap conditions is therefore short and typically restricted to a few days, making this format appropriate only for high-turnover retail systems. As storage progresses, oxymyoglobin is gradually oxidized to metmyoglobin, causing brown discoloration that consumers often interpret as a sign of spoilage [20]. These changes are further intensified by continuous display lighting, which accelerates myoglobin oxidation even when temperature is properly controlled [24]. Moreover, while PVC films offer moderate moisture protection, they cannot completely prevent fluid accumulation if the product exhibits low water-holding capacity. The presence of moist absorbent pads may, in turn, create localized environments favorable to microbial growth [25].

For these reasons, overwrap packaging is suitable mainly for short supply chains and rapid retail turnover. In practice, it is sometimes used strategically after bulk storage under VP or MAP, with meat being repackaged into overwrap format at retail level to restore visual appeal immediately before sale [32], [33]. This hybrid approach combines the preservative efficiency of low-oxygen systems with the display advantages of oxygen-permeable packaging. Nevertheless, overwrap packaging remains inherently limited in terms of oxidative and microbiological stability, particularly for high-fat meats or products intended for prolonged refrigerated distribution.

Vacuum packaging

Vacuum packaging is based on the removal of ambient air followed by sealing in a film with low gas permeability, thereby generating an anaerobic environment that suppresses oxidative reactions and restricts the growth of aerobic spoilage microorganisms [20]. This system effectively delays lipid peroxidation and pigment oxidation, both of which are central to rancidity development and color deterioration. As oxygen levels decline, deoxymyoglobin becomes the dominant pigment form, resulting in the characteristic purplish-red appearance associated with vacuum-packed meat [28].

At the physicochemical level, reduced oxygen availability also slows protein oxidation, including the conversion of sulfhydryl groups into disulfides and the aggregation of myofibrillar proteins, which are processes linked to loss of tenderness and decreased water retention [34]. By reducing oxidation and purge-related reactions, VP contributes to improved structural stability during storage. However, prolonged anaerobic storage may also influence endogenous enzymatic reactions involved in flavor development, leading to subtle sensory differences compared with meat stored under oxygenated conditions.

Microbiologically, VP effectively suppresses aerobic spoilage organisms such as *Pseudomonas spp.* and molds. However, psychrotrophic facultative anaerobes and obligate anaerobes, including *Clostridium* spp., may persist if storage temperature is inadequately controlled. Therefore, cold-chain integrity remains essential, even under vacuum conditions. To further strengthen VP performance, oxygen scavengers have been incorporated into some systems to lower residual O_2 to very low levels, thereby improving inhibition of aerobic microbes and extending color stability [19]. Such improvements are particularly relevant in products like fresh sausages, where reduced psychrotrophic growth has been documented when scavengers are used in combination with low-oxygen packaging.

One of the main limitations of VP remains consumer perception. Although the purplish color is chemically stable and not indicative of poor eating quality, its acceptance varies according to product type and market context [15]. For high-value red meats, visual appearance may therefore reduce direct retail suitability unless a blooming step is used before display. This limitation has led to practical hybrid systems in which meat is transported and stored under vacuum, then exposed to air or repackaged in high-O_2 MAP for sale.

From an operational perspective, the effectiveness of VP depends not only on evacuation efficiency but also on headspace conditions and film barrier properties. Even small amounts of residual air may have disproportionate effects on oxidative stability if temperature fluctuates during storage or transport. Similarly, insufficiently impermeable films may allow gradual oxygen ingress, compromising pigment chemistry and aroma stability over time. For these reasons, multilayer films with improved gas barrier properties, including nanocomposite-based materials, are increasingly being investigated as a means of strengthening VP performance without fundamentally altering its preservation mechanism [10], [35].

Overall, vacuum packaging remains one of the most reliable conventional systems for extending the chilled shelf-life of fresh meat, typically from 5–7 days under refrigeration alone to approximately 10–14 days when vacuum conditions are properly maintained [19]. Its practical value is particularly evident in regional or medium-distance distribution chains, where oxidative stability and microbial suppression are prioritized over immediate retail color appeal.

Modified atmosphere packaging

Modified atmosphere packaging is based on the deliberate adjustment of gas composition in the package headspace, typically through combinations of O_2, CO_2, and N_2, in order to modulate both microbial and physicochemical changes during refrigerated storage. In red meat systems, oxygen is frequently included to stabilize oxymyoglobin and preserve a bright red appearance, while carbon dioxide is used primarily for its bacteriostatic effect. Nitrogen serves as an inert filler gas that prevents package collapse when CO_2 dissolves into the product [21].

The performance of MAP depends directly on the proportions of these gases. High-O_2 atmospheres-often above 50% O_2-support retail color stability, but they also intensify oxidative stress, promoting lipid oxidation, protein cross-linking, and generation of rancid volatiles [22]. These reactions may reduce tenderness, affect water-holding capacity, and shorten the sensory shelf-life despite initially favorable appearance. By contrast, high-CO_2 atmospheres are more effective for suppressing aerobic spoilage flora such as *Pseudomonas spp.* and other Gram-negative psychrotrophs [37]. However, excessive CO_2 may lower pH at the meat surface, induce protein denaturation, increase drip loss, and alter flavor, especially in moisture-rich products [23].

In practice, balanced gas mixtures are often used to combine the advantages of both preservation mechanisms. For example, certain lamb packaging systems employ mixtures such as 80:20:0 O_2:CO_2:N_2, which provide both microbial control and acceptable color retention. Likewise, low-O_2/high-CO_2 atmospheres are preferred when oxidative stability is more important than retail redness, such as in processed meats or sausages [16]. In these cases, the reduction in oxygen availability greatly limits lipid peroxidation and supports longer flavor stability.

Several additional factors influence MAP effectiveness. Headspace-to-product ratio affects gas diffusion and microbial suppression, while film permeability determines the extent to which the initial gas mixture can be maintained over time [22]. This is especially important because microbial activity, tissue respiration, and gas diffusion may alter internal atmospheres during storage. To address this, dynamic MAP systems have been proposed, incorporating oxygen scavengers and CO_2 emitters capable of correcting atmosphere drift during distribution [27]. Such systems are particularly promising for stabilizing preservation conditions when seal integrity or environmental conditions vary.

The physicochemical consequences of MAP are closely linked to gas composition. High-O_2 MAP maintains attractive redness in the early phase of storage, but often at the cost of accelerated oxidation and eventual browning once oxidative thresholds are exceeded [15], [40]. Low-O_2/high-CO_2 systems, on the other hand, better preserve lipid stability and flavor but may result in a darker or purplish appearance due to deoxymyoglobin prevalence. This creates a persistent trade-off between visual attractiveness and chemical stability. Balanced mixtures, generally in the range of 20–40% O_2 and 40–60% CO_2, have shown promise in moderating both aerobic spoilage and oxidative deterioration without strongly compromising either color or texture [42].

Taken together, MAP is a highly versatile system whose success depends on precise adaptation to meat type, lipid profile, intended distribution chain, and consumer expectations. No single gas composition universally optimizes all quality parameters; rather, packaging design must be tailored to the physicochemical and microbiological behavior of the specific product. Emerging MAP systems incorporating active components appear especially promising because they can counterbalance some of the limitations inherent to static gas mixtures, thereby offering more stable preservation conditions across extended refrigerated storage.

4. ADVANCED PACKAGING TECHNOLOGIES: ACTIVE AND INTELLIGENT SYSTEMS

As preservation requirements have become more demanding, conventional packaging systems have increasingly been complemented by more sophisticated solutions capable of either directly modulating the package environment or continuously monitoring product status during storage and distribution. Within this context, active and intelligent packaging technologies represent two of the most important directions in modern refrigerated meat preservation. While active packaging acts directly on spoilage pathways, intelligent packaging primarily serves as an information-based tool that improves quality management, traceability, and decision-making throughout the supply chain [43], [46].

Active packaging

Active packaging (AP) for refrigerated meat is based on the incorporation of functional elements into the packaging matrix, or into components embedded within the package, with the aim of directly interacting with the product environment and extending shelf-life. Unlike conventional passive systems, which mainly act as physical barriers, AP is designed to modify the internal atmosphere over time by releasing, absorbing, or regulating compounds associated with spoilage processes [44]. In this sense, AP should be understood not as a single technology, but as a group of strategies targeting oxidative stability, microbial control, and moisture management.

One of the most established AP functions is oxygen scavenging. These systems, frequently based on iron-containing powders incorporated into sachets, labels, or patches, remove residual oxygen remaining after packaging or diffusing through film barriers during storage. Lowering oxygen concentration below critical thresholds delays lipid peroxidation, helps preserve myoglobin in its reduced forms, and suppresses the growth of aerobic microorganisms. However, the effectiveness of these systems is highly dependent on scavenging kinetics. Some earlier iron-based systems require several days to achieve complete oxygen removal, which may be suboptimal for highly perishable thawed meat products where rapid microbial proliferation can occur [20]. By contrast, newer high-efficiency scavengers have demonstrated substantially faster action, reducing oxygen levels within hours rather than days [19].

A second major AP strategy involves the incorporation of antioxidants into packaging materials. Both natural compounds-such as rosemary extracts, polyphenols, or protein-based matrices derived from by-products like mango peel-and synthetic agents may be used to intercept free radicals before they initiate oxidative chain reactions in lipids and proteins [8], [10]. These antioxidants can be incorporated into multilayer films, coatings, or electrospun fibers with high surface area, allowing more responsive release in the presence of moisture, temperature fluctuations, or other environmental triggers. Their function is particularly valuable under high-O_2 MAP conditions, where color retention is desirable but oxidation risk is elevated. In such systems, antioxidant-based AP can delay rancidity development, limit pigment oxidation, and improve the stability of flavor and aroma during storage.

Antimicrobial active packaging constitutes another major area of development. These systems rely on the incorporation or controlled release of compounds capable of suppressing spoilage and pathogenic microorganisms on the meat surface and within the package headspace [11]. Such agents include essential oils, organic acids, enzymes with membrane-targeting activity, and, in some cases, nanoparticles such as TiO_2, which may exert photocatalytic antimicrobial effects [18]. A key advantage of these systems lies in their ability to reach localized niches that conventional atmospheres cannot fully control, including purge accumulation zones and film–meat interfaces. Controlled-release packaging is particularly advantageous because it sustains antimicrobial activity over time rather than delivering an immediate but short-lived effect.

Moisture regulation is another relevant AP mechanism, although it is often less emphasized than oxygen control or antimicrobial release. Through the use of desiccants, absorbent pads, or humidity-regulating composite films, AP systems can help maintain water activity below levels favorable for microbial growth while minimizing excessive drip loss and preserving textural quality. Such systems also reduce the accumulation of exudate, which is not only undesirable from a visual standpoint but also provides a substrate for microbial proliferation and oxidative deterioration [19].

Recent research increasingly focuses on multifunctional AP systems that combine several of these mechanisms within a single packaging structure. Hybrid films or composite systems integrating oxygen scavengers, antimicrobial compounds, antioxidants, and even CO_2-releasing components are particularly promising [44]. These systems act simultaneously on multiple spoilage pathways, improving oxidative stability, delaying microbial growth, and, in some cases, stabilizing package geometry by compensating for gas absorption during storage. This multifunctional approach is especially relevant in dynamic MAP systems, where active elements can help correct gas shifts associated with respiration, temperature fluctuations, or imperfect seals.

From an industrial perspective, the value of AP depends not only on efficacy but also on product type and distribution scenario. High-fat meats benefit particularly from antioxidant-enriched systems because oxidation is a major shelf-life determinant, whereas leaner meats stored under low-O_2/high-CO_2 atmospheres may benefit more from antimicrobial strategies directed against psychrotrophic anaerobic or facultative anaerobic populations [11]. Although multilayer AP systems with controlled release properties are generally more expensive than conventional packaging formats, their contribution to shelf-life extension and food waste reduction may compensate for initial costs, especially in long or complex distribution chains [8].

Material science also plays an important role in AP development. Nanocomposite incorporation has been shown to improve both mechanical resistance and barrier properties without substantially increasing film thickness. For example, TiO_2-based nanocomposite films have been associated with lower microbial counts and reduced lipid oxidation in refrigerated lamb, while also preserving sensory quality during extended storage [18]. Similarly, natural compounds such as garlic extract have demonstrated antimicrobial efficacy through allicin-mediated disruption of bacterial cell wall permeability and enzyme systems, extending the shelf-life of chilled beef beyond that of untreated controls [45]. Importantly, when such natural antimicrobial systems are combined with freshness indicators, they may give rise to dual-function packaging concepts that both delay deterioration and visually communicate product status [45].

Overall, the development of active packaging reflects a shift away from single-function preservation tools toward broader systems-level control of refrigerated meat stability. Rather than simply minimizing one spoilage pathway, current AP research increasingly aims to coordinate multiple preservation functions within the same material platform. Nonetheless, important constraints remain. These include cost, scale-up challenges, regulatory considerations related to migration and food contact safety, and the need to calibrate active release so that preservation benefits are not offset by sensory drawbacks, such as excessive acidification or overpowering aromas from essential oils [10]. Even so, AP remains one of the most promising technological directions for extending refrigerated meat shelf-life in a targeted and adaptive manner.

Intelligent packaging

Whereas active packaging modifies the product environment, intelligent packaging focuses on observation, detection, and communication. It is designed to provide information on product condition, storage history, or packaging integrity rather than directly preventing spoilage [46]. In refrigerated meat systems, intelligent packaging represents a major step toward data-driven preservation, enabling stakeholders to move from static shelf-life assumptions to real-time quality assessment and more responsive inventory management [43].

The most widely discussed intelligent packaging tools include time–temperature indicators (TTIs), gas sensors, freshness indicators, and integrity sensors. Each of these responds to a different aspect of the spoilage process. TTIs are among the most practical and commercially relevant systems because they record cumulative thermal exposure over time. Since microbial growth under refrigeration is highly dependent on temperature history, TTI responses can be correlated with predictive microbial models, allowing a more accurate estimation of remaining shelf-life than fixed expiry dates alone. Their main value lies in detecting cold-chain breaks during transport, retail storage, or handling, thereby enabling products at elevated risk to be identified before visible spoilage occurs.

Gas sensors operate by detecting changes in headspace composition, especially fluctuations in O_2, CO_2, or volatile organic compounds generated by microbial metabolism or oxidative reactions. In refrigerated meat, such changes often precede obvious sensory deterioration. For example, a decline in O_2 accompanied by rising CO_2 may indicate microbial activity or altered respiration patterns, while oxygen ingress may signal package failure and increased oxidation risk. Because these changes are measurable before severe discoloration or odor development becomes apparent, gas sensors are particularly useful for early quality intervention [46].

Freshness indicators usually rely on colorimetric systems sensitive to changes in pH or the accumulation of volatile amines and other spoilage metabolites [6]. Natural pigments such as anthocyanins, curcumin, alizarin, or betalain-type compounds are often used because they visibly change color in response to chemical shifts associated with spoilage. Their main advantage is immediacy: unlike laboratory tests or instrument-based analyses, they can be interpreted visually by supply-chain operators or consumers without opening the package. In protein-rich foods such as refrigerated meat, where microbial metabolism produces compounds that alter local pH and volatile profiles, these indicators can serve as accessible freshness cues directly linked to biochemical deterioration.

Intelligent packaging becomes even more powerful when linked to broader digital systems. For instance, sensor outputs can be integrated with RFID technology, allowing remote data logging and continuous monitoring during transport and storage [46]. Such systems improve traceability and may be coupled with QR codes, cloud-based databases, or blockchain-supported records to provide end-to-end information from slaughter to retail display. This not only helps identify where spoilage-related failures occur, but also strengthens transparency and consumer trust by making handling history more visible [8].

Unlike active packaging, intelligent systems do not directly alter oxidation rates or microbial succession. Their role is therefore indirect but strategically important. By identifying oxygen ingress, excessive humidity, abnormal temperature exposure, or the onset of volatile metabolite production, intelligent packaging enables faster intervention before product quality declines below acceptable thresholds. In practical terms, this may allow batches to be redirected, prioritized for sale, or removed from circulation earlier than would be possible under conventional date-label systems. Such functionality is particularly valuable in complex or long-distance supply chains, where environmental conditions are more variable and quality loss may be unevenly distributed across inventory.

From a microbiological standpoint, intelligent systems offer an important advantage over traditional quality control because they shorten the feedback loop. Some biosensors are capable of indicating spoilage-related changes before colony counts reach conventional rejection levels, providing a preventive rather than reactive management tool [11]. This is especially relevant in meat packaged under vacuum or low-oxygen conditions, where visual spoilage signs may be delayed while microbial or fermentative activity continues to progress. In such scenarios, sensor-based monitoring may compensate for the limitations of appearance alone as an indicator of product safety or quality.

There is also a growing interest in combining intelligent and active functions into hybrid systems. One example is the integration of halochromic freshness indicators into antimicrobial films, allowing a single package to both inhibit spoilage and signal whether spoilage is still progressing as expected [8]. This type of combined system links intervention and monitoring within a single material architecture, representing one of the most promising future directions in meat packaging. Biosensors based on nanostructured materials have shown particularly high sensitivity and rapid signal transduction, suggesting industrial potential if production costs can be reduced sufficiently (Figure 2).

Nevertheless, several challenges still limit large-scale adoption of intelligent packaging. Sensor fabrication may increase the environmental footprint of packaging systems, particularly when electronics or batteries are involved. In addition, some sensor systems require calibration, specialized readers, or infrastructure investments that may not be feasible across all retail or distribution settings. Even colorimetric systems, although simple in principle, may respond too slowly at very early spoilage stages or may show reduced reliability under fluctuating humidity and lighting conditions. Consequently, future progress in this field will depend not only on analytical performance but also on cost reduction, simplification, and compatibility with sustainable packaging materials [44].

Fig. 2 .Illustration of intelligent packaging systems for real-time monitoring and traceability of refrigerated meat quality *(created using NotebookLM and Canvas)*

Taken together, intelligent packaging represents a fundamental transition in refrigerated meat preservation-from packaging as a passive container or reactive barrier to packaging as an active information platform. When properly integrated with conventional or advanced preservation systems, intelligent technologies allow quality management to become more dynamic, precise, and transparent. Their long-term value lies less in replacing existing preservation methods than in enhancing the ability of supply chains to detect, interpret, and respond to product deterioration in real time.

5. MICROBIOLOGICAL STABILITY, SENSORY QUALITY AND SHELF-LIFE

Microbiological stability and safety

Microbiological stability under refrigerated conditions is strongly influenced by the way packaging systems shape ecological niches for spoilage organisms and potential pathogens throughout storage. The primary objective of preservation is not only to delay sensory rejection, but also to prevent microbial proliferation beyond safety thresholds during the intended shelf-life. Packaging atmospheres, barrier properties, and active functionalities modulate microbial growth through combined effects on oxygen availability, moisture, pH, and antimicrobial exposure [23].

In high-O_2 modified atmosphere packaging (MAP), aerobic spoilage organisms such as *Pseudomonas spp.* dominate early storage due to favorable oxygen conditions [34]. These microorganisms generate slime and off-odors, serving as practical spoilage indicators, while also competing with anaerobic species. In contrast, CO_2-rich MAP suppresses aerobic flora by lowering surface pH through CO_2 dissolution, shifting microbial populations toward facultative anaerobes such as *Lactobacillus spp.* [8], [47]. These bacteria generally grow more slowly and may contribute to a more gradual deterioration process.

Vacuum packaging (VP) induces a similar microbial shift toward lactic acid bacteria but may allow survival of psychrotrophic anaerobes, including *Clostridium* species, particularly when temperature control is inadequate [48]. This highlights the importance of initial hygiene and strict cold-chain management, as packaging alone cannot compensate for high contamination levels.

Active packaging enhances microbiological control by integrating antimicrobial compounds directly into the packaging system. Essential oils, polyphenols, and enzyme-based systems can disrupt microbial cell structures and inhibit growth across both surface and headspace environments [11], [33]. Oxygen scavengers further reduce aerobic growth by eliminating residual oxygen, while antimicrobial coatings extend lag phases even under low-O_2 conditions [23]. These mechanisms contribute to delaying spoilage onset and reducing microbial load progression.

Intelligent packaging supports microbiological safety indirectly through early detection. Biosensors responsive to volatile amines or pH shifts can signal microbial activity before sensory rejection becomes evident [13]. Time–temperature indicators (TTIs) allow correlation between temperature history and microbial growth, enabling more accurate estimation of remaining shelf-life [8]. These tools are particularly relevant in systems where visual cues are delayed, such as VP or low-O_2 MAP.

Microbial shelf-life is ultimately determined by the time required for populations to reach critical thresholds. Overwrap systems favor rapid aerobic growth and short shelf-life (3–5 days), while VP extends storage to approximately 10–14 days. High-CO_2 MAP may further prolong shelf-life to 14–21 days under optimal conditions, especially when combined with active antimicrobial systems [11], [23], [44].

Recent approaches combine atmospheric control with active antimicrobial strategies to enhance safety. For example, lactoperoxidase-based systems integrated into CO_2-rich MAP reduce microbial loads while maintaining sensory quality [49]. However, effectiveness varies depending on species-specific resistance, as certain pathogens such as *Listeria monocytogenes* require combined interventions for adequate control [33].

Overall, microbiological stability results from the interaction between packaging conditions, intrinsic product properties, and external factors such as temperature and hygiene. Effective preservation strategies therefore require an integrated approach combining atmosphere control, antimicrobial intervention, and monitoring systems.

Sensory quality and shelf-life

Sensory quality represents a critical determinant of refrigerated meat acceptability and is closely linked to physicochemical and microbiological changes during storage. Attributes such as color, flavor, aroma, texture, and juiciness evolve continuously and define the practical shelf-life from a consumer perspective.

Color is often the primary factor influencing purchase decisions. High-O_2 MAP maintains oxymyoglobin and a bright red appearance, which is strongly associated with freshness [25]. However, this benefit is offset by increased oxidative degradation over time, leading to metmyoglobin formation and browning, particularly under light exposure [24]. In contrast, VP and low-O_2 MAP reduce oxidation but result in a darker, purplish color due to deoxymyoglobin, which may be perceived less favorably despite higher chemical stability [15], [23].

Active packaging systems incorporating antioxidants help delay pigment oxidation and extend color stability even in oxygen-rich environments [8]. These systems reduce oxidative stress and allow better preservation of visual quality without accelerating degradation processes.

Flavor and aroma are largely determined by lipid oxidation and microbial metabolism. Oxidative degradation produces aldehydes and ketones responsible for rancid notes, especially in oxygen-rich environments such as overwrap packaging [20]. VP and low-O_2 systems significantly reduce these reactions, while antioxidant-based AP further limits radical formation and preserves flavor integrity [8], [23].

Microbial metabolism also contributes to sensory changes. Lactic acid bacteria in low-O_2 environments may produce mild acidic notes, whereas aerobic spoilage organisms such as *Pseudomonas* generate sulfur compounds associated with off-odors [33]. Intelligent packaging capable of detecting volatile compounds can help identify early sensory deterioration and support quality control decisions [46].

Texture is influenced by protein stability and water-holding capacity. High CO_2 levels may cause protein denaturation and increased purge, negatively affecting juiciness [23]. VP generally preserves texture better by limiting oxidation without significant pH changes, while moisture-regulating AP systems help stabilize drip loss and maintain structural integrity [19].

In practical terms, sensory shelf-life is often shorter than microbiological safety limits. Overwrap packaging provides strong initial color but limited shelf-life (3–4 days). VP extends acceptable sensory quality to approximately 10–12 days, while CO_2-rich MAP may reach 13–20 days depending on conditions. Hybrid systems combining MAP or VP with active packaging can extend sensory acceptability to 18–25 days under controlled storage [11], [23], [42].

Shelf-life optimization therefore requires balancing visual appeal, flavor stability, and texture retention with microbial safety. Packaging strategies must be adapted to market requirements: short distribution chains favor high-O_2 systems for appearance, whereas long-distance supply chains benefit from low-O_2 or hybrid systems that prioritize overall stability.

6. FUTURE DIRECTIONS IN MEAT PACKAGING

Future developments in refrigerated meat packaging are oriented toward integrated systems that combine preservation, monitoring, and sustainability. Active and intelligent technologies are increasingly converging into multifunctional platforms capable of both controlling and tracking product quality throughout the supply chain [44], [50].

A key direction involves the development of "active-green" materials that integrate antimicrobial and antioxidant functions into biodegradable or bio-based matrices [8]. These systems aim to reduce environmental impact while maintaining or improving preservation efficiency. Such approaches are particularly relevant given increasing regulatory and consumer pressure for sustainable packaging solutions.

Dynamic MAP systems represent another important innovation. Unlike static gas mixtures, these systems use scavengers or emitters that respond to environmental changes, maintaining stable internal conditions during storage [27]. This adaptability helps address gas composition drift caused by respiration, permeability, or temperature fluctuations.

Advances in sensor technology are also driving progress in intelligent packaging. Printable biosensors based on natural pigments offer low-cost, visually interpretable indicators of spoilage-related changes [19], [46]. Their integration into packaging materials may enable broader adoption of real-time monitoring without complex infrastructure.

Nanocomposite materials are being explored for improving barrier properties and mechanical strength, allowing longer shelf-life without compromising sensory quality [18]. Additionally, predictive modeling combined with sensor data may enable product-specific optimization of packaging conditions based on factors such as fat content, cut type, and distribution conditions [20].

Integration with digital technologies such as RFID, IoT, and blockchain further enhances traceability and supply chain transparency, enabling better quality management and consumer confidence [44]. These systems support data-driven decision-making and more efficient inventory control (Figure 3).

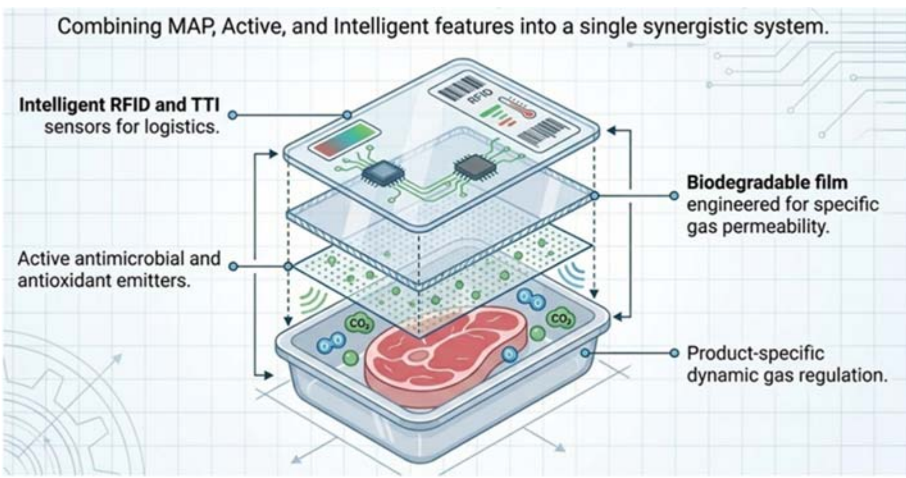

Fig. 3. Illustration of an integrated packaging system combining modified atmosphere packaging (MAP), active, and intelligent components for optimized preservation of refrigerated meat.*(created using NotebookLM and Canva)*

Future packaging systems are expected to evolve into adaptive platforms that combine atmosphere control, active preservation, intelligent monitoring, and sustainability considerations.

CONCLUSION

Refrigerated meat preservation is a complex process that requires the coordinated control of microbial activity, oxidative reactions, and sensory quality. Conventional packaging systems such as vacuum packaging and modified atmosphere packaging remain fundamental tools for extending shelf-life by regulating oxygen exposure and microbial growth.

Active packaging enhances these systems by introducing functional components that directly mitigate spoilage processes, while intelligent packaging provides real-time monitoring and supports more efficient quality management. Together, these technologies contribute to a more dynamic and responsive preservation approach.

The effectiveness of packaging strategies depends on both intrinsic product properties and extrinsic storage conditions. Factors such as composition, temperature, humidity, and handling significantly influence preservation outcomes, emphasizing the need for integrated cold-chain management.

Emerging trends indicate a shift toward multifunctional and sustainable packaging solutions that combine active and intelligent features within advanced materials. These innovations offer improved shelf-life, enhanced safety, and reduced food waste while addressing environmental concerns.

In conclusion, optimizing refrigerated meat preservation requires a holistic approach that integrates packaging technology, product characteristics, and supply chain conditions. Continued advancements in materials, active systems, and monitoring technologies will support more efficient, sustainable, and reliable preservation strategies in the meat industry.

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