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Review

Active Packaging Applications in Meat and Meat Products

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Abstract

Meat is highly perishable and has a short shelf life, and it can easily spoil, which can be prevented through alternative packaging methods. Packaging can be helpful not only during transportation but also in extending the shelf life and enhancing the quality, flavor, and taste of food. As demand for food safety, quality, and environmental protection continues to grow, active food packaging is becoming increasingly important in the food industry to address emerging challenges. This review summarizes major active packaging strategies for meat preservation, including oxygen scavenging, moisture regulation, carbon dioxide release, antioxidant, and antimicrobial systems. It also examines the application of bio-based materials, plant-derived bioactives, nanotechnology, and controlled-release mechanisms to enhance product safety, quality, and sustainability. The integration of active packaging technologies shows strong potential to extend shelf life and ensure the safety of fresh and processed meat products.

Keywords: Active Packaging, Shelf-life Extension, Quality Improvement.

Introduction

Meat is renowned for its nutritive value but faces persistent hurdles in preservation. The lack of preservation methods can lead to meat deterioration, resulting in significant economic losses for the food and meat industries each year and undermining consumer confidence. Consequently, both economic losses and litigation costs faced by these industries continue to rise steadily. For the preservation of meat and meat products, a wide range of synthetic and natural antimicrobials and antioxidants have been consistently used. Khan *et al.* (2020) explained that these substances are applied directly to the meat surface or used in combination with edible films and coatings, commonly known as active packaging.

The concept of active packaging has evolved as a promising solution to overcome the limitations of traditional packaging systems, particularly in the meat industry, where perishability and microbial spoilage are key concerns (Cenci-Goga *et al.*, 2020). As a result, there is a growing need for packaging materials and methods that provide robust protection against spoilage and pathogenic microorganisms, minimize oxygen exposure, and maintain optimal moisture control (Ju, 2025; Figueroa-Enríquez *et al.*, 2024). Active packaging involves the intentional inclusion of components that release or absorb substances to extend shelf life or maintain/improve food condition. Therefore, this review presents various active packaging methods used to preserve meat and meat products.

Oxygen Scavengers

These are designed to remove residual or ingress oxygen from the packaging headspace. Iron-based systems are the most widely used oxygen scavengers in meat packaging. The application of oxygen scavengers (OS) has become one of the most important active packaging technologies, as they can remove oxygen from food packages and improve barrier properties by acting as an active barrier. A non-ferrous oxygen scavenger (NFOS) composed of activated carbon and sodium L-ascorbate was developed and evaluated for raw meat loaf, demonstrating suppressed lipid oxidation and reduced microbial growth (Lee *et al.*, 2018). An oxygen scavenger reacts with oxygen to eliminate residual oxygen within the package while preventing oxygen from entering the surrounding environment (Arfan *et al.*, 2026).

Moisture Regulators

Active packaging is an advanced form of packaging that interacts with the food product to extend shelf life, improve safety, and maintain quality. Moisture-regulating systems in active packaging—such as absorbers, emitters, and humidity-buffering films—play a crucial role in maintaining product quality and extending shelf life for perishable foods like meat (Sivakanthan & Natchimuthu, 2020). Moisture absorbers like silica gel and calcium chloride remove excess moisture, while moisture emitters release humidity when the air is too dry. Humidity-buffering films can both absorb and release moisture to maintain balance, and active pads or sachets inside packaging absorb liquids or add moisture as needed. By regulating moisture, these applications prevent spoilage and improve product quality. Electrospun PVOH packaging containing laurel and rosemary essential oils effectively reduced moisture sensitivity, inhibited microbial growth and lipid oxidation, and extended the shelf life of chicken breast (Goksen *et al.*, 2021).

Carbon Dioxide Emitters

Modified atmosphere packaging containing CO_2 is commonly used to extend the shelf life of meat and meat products. As an alternative to traditional MAP, active packaging incorporates CO_2 emitter sachets into meat packages (Cenci-Goga *et al.*, 2020). There are moisture-regulated carbon dioxide emitters, such as sodium bicarbonate and citric acid, as well as film-based emitters and carbon dioxide-releasing gels. Since CO_2 is a microbial inhibitor, CO_2 emitters also inhibit microbial growth and increase shelf life. CO_2 emitter pads rapidly released carbon dioxide, inhibited aerobic microbial growth, maintained the package atmosphere, and effectively extended the shelf life of refrigerated beef, as reported by Mortazavi *et al.* (2024).

Antioxidants and Antimicrobials

Antioxidant active packaging systems can effectively reduce lipid oxidation in meat, preventing rancidity and color degradation. Various antioxidant compounds—including rosemary extract, tocopherols, ascorbic acid, and other plant-derived extracts—can be incorporated into bio-based films to minimize oxidative reactions in meat products

(Shahidi & Zhong, 2010; Falguera *et al.,* 2011). Chitosan-based microcapsules and other biopolymers, such as cellulose and starch, also serve as suitable carriers for delivering these antioxidants—for example, butylated hydroxyanisole (BHA), butylated hydroxytoluene (BHT), mono-tert-butyl hydroquinone (TBHQ), and propyl gallate (PG)—which help reduce oxidation and enhance shelf life in meat and meat products. Antimicrobial substances incorporated into packaging materials can reduce microbial growth, extend lag phases, or inactivate target organisms (Coma, 2013; Realini & Marcos, 2014). Such antimicrobial active packaging systems can significantly extend shelf life and reinforce the safety and quality of fresh meat and meat products (Ramos et al., 2020). Chitosan films containing coconut and palm kernel oils exhibited strong antimicrobial and antioxidant activity, extending the shelf life of beef steak (Hoa *et al.,* 2022). A zein fiber-based active meat tray incorporating thyme essential oil effectively inhibited the growth of thermotolerant coliforms, Escherichia coli, and Staphylococcus species during refrigerated storage, thereby extending the shelf life of the packed meat (Peixoto *et al.,* 2023).

Active packaging containing synthetic antioxidants can protect the meat from lipid oxidation, but an increase in consumer demand is leading to. Still, rising consumer demand is driving the use of natural rather than artificial antioxidants. Essential oils are used instead of synthetic ones, which have the disadvantage of a strong odor (Zhang *et al.,* 2022). Nanotechnology presents a simple, sustainable, and cost-effective approach to address these challenges, in which reducing particle size to a new range will enhance antimicrobial properties and mask the strong odor. This advanced technology plays a vital role in enhancing the production, storage, processing, transportation, and safety of meat products. Therefore, reducing the microbial load and maintaining the quality and safety of meat products.

Antimicrobial Films and Coatings as Active Packaging

Zhang *et al.* (2022) defined an active food-packaging film as a pre-shaped, free-standing layer composed of functional materials, whereas they described an active coating as an edible, thin film formed directly on the surface of food, typically applied by dipping or spraying with a film-forming solution. Edible films are applied directly to the surface of food products and function as primary edible packaging, typically ranging from 50 to 250 µm in thickness, and are used to wrap foods, form pouches or bags, or be positioned between layers of food (Kumar *et al.*, 2022). In contrast, edible coatings—although also thin layers of edible materials—are applied in liquid form with varying viscosities and are spread onto the surface or between layers of food by spraying, dipping, or brushing (Hamed *et al.,* 2022). These coating systems are commonly used on various food items (Kumar *et al.,* 2022). The development of film using eco-friendly ways is increasing, with extracts from plants, including roots, stems, leaves, flowers, and fruits, widely used in the food and pharmaceutical industries due to their rich content of antioxidant compounds like polyphenols and flavonoids.

A moisture-activated antimicrobial film incorporating ground mustard seeds was developed and successfully applied as an active packaging system for meat products (Bahmid *et al.,* 2021). Green tea extracts are commonly utilized in edible films and coatings due to their rich content of bioactive compounds, including catechins, epicatechins, epigallocatechins, and gallic acid (Lorenzo & Munekata, 2016). The antimicrobial effectiveness of thyme (*Thymus vulgaris*) essential oil encapsulated in zein fiber for use in meat trays as an active packaging solution was investigated by Peixoto *et al.* (2023). Similarly, Zhang *et al.* (2020) prepared active packaging films using plant-based extracts such as pine nutshell, peanut shell, and winter jujube leaf incorporated into chitosan films, thereby increasing the film thickness.

Role of Active Packaging Film and Coatings in Livestock Products

Microbial Inhibition

Antimicrobial active agents (nisin, lysozyme, essential oils, bacteriocins, metal nanoparticles) reduce viable counts by disrupting membranes, inhibiting cell wall synthesis, or interfering with metabolism. Contact films (e.g., chitosan) provide a surface hostile to microbes, whereas release systems deliver agents to the meat surface or headspace to suppress spoilage and pathogenic bacteria (Gaba *et al.,* 2023). Controlled release prolongs activity and can reduce the required dose for microbial inhibition.

Oxidation Control

Lipid oxidation in red meat and poultry causes rancidity, color deterioration, and nutrient losses. Incorporating antioxidants into packaging films, either synthetic or natural (phenolics, tocopherols, plant extracts), helps scavenge free radicals and chelate pro-oxidant metals (Rojas & Brewer, 2020).

Moisture and Gas Control

Moisture absorbers reduce drip and microbial niches, while oxygen scavengers limit aerobic spoilage and pigment oxidation. AP that modulates headspace composition (e.g., oxygen absorbers + CO_2 emitters) complements modified atmosphere packaging (MAP), improving color retention and reducing aerobic microbial load.

Practical Applications of Active Packaging in Livestock Products

Fresh Red Meat and Poultry

Edible antimicrobial/antioxidant films or coated casings applied to fresh steaks, minced meat, or poultry cuts have demonstrated reduced microbial growth and delayed lipid oxidation during chilled storage, preserving color and sensory quality (Gaba, Mahmoud, & El-Tantawy, 2023).

Minced/Processed Meats and Ready-to-eat (RTE) products

Minced meats are especially vulnerable due to increased surface area. AP coatings with controlled release of antimicrobials or antioxidants reduce spoilage organisms and can limit Listeria growth in RTE products. Incorporating nisin and essential oils into polymer films or sachets has been beneficial for hurdle approaches.

Cured and Fermented Meats

Active packaging targeting lipid oxidation (antioxidant release) prolongs flavor stability in cured meats; antimicrobials must be carefully balanced to avoid interference with desirable fermentation microflora. Intelligent indicators (pH/color) help monitor spoilage or the progress of fermentation.

Controlled-Release Technologies and Kinetics in Active Packaging

Controlled-release packaging (CRP) regulates the release rate of bioactives to align with the product's deterioration kinetics. Controlled-release packaging technologies rely on encapsulation systems, multilayer films, and nanocomposites, with release behavior governed by polymer structure, polarity, temperature, and headspace conditions (Kurek *et al.*, 2018). Research has also begun to explore stimuli-responsive release—such as pH- or enzyme-triggered release.

Research Trends and Future Directions

The use of nanotechnology and nanocomposites using eco-friendly materials will enhance mechanical strength, improve barrier properties, and control the release of bioactive substances, which is a very new area of research in the field of active packaging. Targeted microbial control using phage probiotics is also a growing active packaging application. Further, the combination of active packaging with fresh sensors and traceability application is a novel area of research in this field. Natural extracts, including citrus, propolis, mustard, garlic, green tea, Origanum *vulgare*, rambutan, and *Zataria multiflora,* reduce oxidation, inhibit microbes, and extend meat shelf life, as reported by Iqbal (2023). A chitosan film containing a 2% thyme essential oil nanoemulsion effectively preserved raw chicken by reducing microbial growth and oxidation, maintaining meat quality, and extending its refrigerated shelf life up to 15 days, making it a promising eco-friendly active packaging method as reported by Bhattacharya *et al.* (2025). Mango peel-derived carbon dots improved the strength, antioxidant, antimicrobial, and UV-barrier properties of chitosan/fish gelatin films, extending the shelf life of refrigerated minced pork, as reported by Ponnusamy *et al.* (2025). Similarly, Smaoui *et al.* (2022) reported that essential oil-based active films represent a promising, environmentally friendly approach to extending the shelf life of meat products.

Conclusion

In response to growing consumer demand, packaging systems in the meat industry have undergone significant transformation and innovation in recent decades. To meet these evolving needs, various advanced technologies such as nanotechnology and active packaging incorporating antimicrobial and antioxidant agents have been employed to enhance microbial safety, reduce oxidative spoilage, and extend product shelf life. Although nanotechnology remains a relatively new field, its application in food packaging is gaining traction and warrants further exploration. Additionally, many of the latest approaches emphasize developing environmentally sustainable materials, including biodegradable and compostable packaging, despite current limitations in achieving mechanical and barrier properties comparable to those of conventional plastics. The development of active packaging systems for meat incorporating nano-encapsulated natural antioxidants or antimicrobial agents aims to significantly extend shelf life while effectively eliminating microbial growth and oxidative spoilage in both fresh and processed meat. Furthermore, there is a need to emphasize the use of bio-based and biodegradable materials, either individually or in combination, and consider the application of edible packaging where appropriate.

Contribution by Authors

All the authors contributed equally to writing the manuscript. The final manuscript was read by all authors and consented to publication.

Conflict of Interests

There is no conflict of interest.

Publisher Disclaimer

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