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REVIEW ARTICLE

New Active and Intelligent Packaging Technologies to Increase the Shelf life of Meat Products

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Abstract

Meat products are highly susceptible to microbial spoilage, oxidation, and quality deterioration because their biological structure is rich in protein, fat, and moisture. Traditional packaging, which serves only a passive protective role, is often inadequate and contributes to significant food waste. In recent years, active and intelligent packaging technologies have emerged as novel approaches to extend shelf life and enhance food safety. Smart packaging technology aims to communicate data regarding the administration and historical storage of food goods to elevate product quality and align with consumer expectations. Meat is a highly perishable food that can cause serious illness if spoiled. Various indicators and sensors have been developed to alert about meat spoilage in the industry. Intelligent packaging systems (IPSs) give consumers real-time information and indicate product status. This review article, based on research up to 2025, examines active packaging systems including antimicrobial, antioxidant, and oxygen-scavenging agents and intelligent systems such as gas sensors, time–temperature indicators, and Radio Frequency Identification (RFID). The application of these technologies to meat products, including red meat, poultry, and processed items, with focus on case studies, shows shelf-life increases of 20–50%. This technology has great potential to become a standard tool in meat quality control and could create a promising future for the industry.

1. Introduction

Meat products are a major source of protein in the global diet, but rapid spoilage caused by the growth of microorganisms such as Pseudomonas spp., Enterobacteriaceae and Salmonella spp., lipid oxidation, and physical changes poses a major challenge. FAO reports that more than 20% of the world's meat production is lost annually due to spoilage (FAO, 2023). Traditional packaging (polyethylene films) acts only as a physical barrier and cannot interact with the internal environment of the package. In contrast, active packaging, which releases or absorbs specific substances, and smart packaging, which enables real-time quality monitoring, offer advanced solutions. These technologies have been developed since the 1990s and made significant progress in recent years through the integration of nanomaterials, natural extracts, and artificial intelligence. Consumers and manufacturers increasingly demand strategies to extend the shelf life of food products and to monitor quality in real time. Recent studies (Ivanov *et al.*, 2025) found that an increase of just 2°C in cold chain temperature can raise the rate of biogenic amine formation by 55%, highlighting the importance of monitoring storage conditions and using reactive packaging. Active packaging methods have

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been used to modify the conditions of packaged food to improve safety and sensory properties and extend its shelf life (Mohebi and Marquez, 2014). Active and smart packaging has emerged as a transformative technology in food preservation, acting as a critical interface to monitor and respond to environmental interactions between packaged products and the surrounding environment (Zhang *et al.*, 2025).

Meat consumption has risen significantly over the past 50 years; the global fresh and processed meat market reached 277.5 million tons in 2020 and is projected to grow to 292.92 million tons by 2027. However, spoilage of meat products can cause economic losses for producers and health risks for consumers. To address this, smart packaging using markers and sensors such as barcodes and radio-frequency tags has been developed to ensure quality control and safety (Sani *et al.*, 2024). Despite significant advances, challenges such as high costs and environmental concerns remain (Mazhari and Mahmoudi-Meymand, 2002). The most commonly used technologies include pH indicators, gas sensors, temperature–time indicators, and RFID (Hidayat *et al.*, 2025). Active and smart packaging, as emerging technologies, can preserve food quality and safety throughout shelf life. These systems employ sensors that respond to environmental changes and are especially useful for meat products (Pourhamzeh, 2002) Nanotechnology offers substantial opportunities for innovative biodegradable packaging, providing improved barrier properties, mechanical strength, and active functions (Mahdoyan-Mehr and Sedaghat, 2002). Smart packaging has strong potential to become standard in the meat industry, particularly through integrating gas sensors and freshness indicators that can extend shelf life by up to 50%. This article reviews the mechanisms, applications, challenges, and future prospects of these technologies for meat products.

2. The Importance of Increasing the Shelf Life of Meat Products

The shelf life of meat products depends on several factors, such as the type of meat (red, white, processed), storage conditions (temperature, humidity) and packaging method. For example, fresh red meat can last only 3–5 days at refrigerated temperature (4°C), while processed products such as sausages may last up to 2 weeks. Modern technologies can increase this time by up to 50%, which is crucial in the global supply chain, especially in developing countries. Furthermore, driven by global trends like consumer demand for natural and sustainable products, the integration of plant extracts and biodegradable materials into packaging has become increasingly important. Smart packaging enables monitoring of food quality, safety, integrity, cleanliness, freshness and purity prior to consumption (Koneti *et al.*, 2023).

3. Active Packaging: Concepts, Types and Mechanisms

Active packaging denotes systems that engage proactively with the contents of the packaging or the ambient environment to sustain the quality of food (Mazaheri and Mahmoudi Meymand, 2024). Recent research indicates that the implementation of such systems in meat products enhances shelf life by mitigating microbial proliferation and oxidative processes. Active packaging encompasses various active components, including desiccants, scavengers, antimicrobial release mechanisms, and antioxidants, which are employed in the vicinity of the food to augment the efficacy of the packaging system (Mohebi and Marquez, 2014). Active packaging has risen to prominence as a revolutionary technology in food preservation, serving as a pivotal interface to monitor and react to environmental interactions between packaged goods and their surrounding environment (Zhang *et al.*, 2025).

4. Types of Active Packaging

4.1. Antimicrobial Systems

These systems serve to suppress the proliferation of bacteria, fungi, and pathogenic microorganisms through the release of antimicrobial compounds. Frequently employed materials encompass nano silver, zinc oxide (ZnO), botanical extracts including essential oils derived from basil and thyme, as well as bacteriocins exemplified by nisin. (Zhang *et al.*, 2025). The operational mechanisms of these compounds encompass the infiltration of the bacterial cell membrane, the induction of oxidative stress, the inhibition of essential enzymatic functions, and the infliction of DNA damage (Hakeem *et al.*, 2020). For instance, agar films infused with silver nanoparticles have demonstrated a reduction in bacterial proliferation while concurrently preserving the aesthetic properties, such as color and texture, of refrigerated beef (Heng *et al.*, 2021). Furthermore, the synergistic application of chitosan film in conjunction with clove essential oil within meat products has effectively suppressed the growth of Pseudomonas spp. and has extended the shelf life from 6 days to 12 days (Mohebi and Marquez, 2014). Anticipated advancements by 2025 entail nanoencapsulation techniques for the controlled release of active agents; for example, polylactic acid films incorporating nano encapsulated thymol have been shown to prolong the shelf life of mutton by as much as 14 days by diminishing total bacterial counts to below 6 log CFU/g. The strategic integration of these antimicrobial agents into polymeric matrices serves to enhance meat safety and is underpinned by standardized evaluation protocols that ensure regulatory compliance and quality assurance (Zhang *et al.*, 2025).

Table 1
Comparison of shelf life of various meat products in traditional and modern packaging.

Type of meat product	Shelf life in traditional packaging (days)	shelf life in active/smart packaging (days)	Percentage of increase
Fresh red meat	3-5	7-10	%50-100
Fresh poultry	4-7	10-14	%50-100
Processed sausage	7-14	14-21	%50
Hamburger	2-4	5-8	%100

Table 2
Types of active packaging and examples.

Type	Common materials	Mechanism	Practical example
Antimicrobial	Nanosilver, ZnO, Nisin, Basil/Thyme essential oils	Penetration into membrane, oxidative stress, DNA degradation	Chitosan film + clove essential oil: Pork shelf life from 6 to 12 days (Mohebi & Marquez, 2014)
Antioxidant/ Oxygen absorber	Rosemary extract, Vitamin E, Iron powder	Preventing lipid peroxidation	Whey protein film + rosemary: MDA <0.5 mg/kg in salami after 90 days (Zhang et al., 2025)
Moisture/Ethylene control	Modified starch, Silica gel	Moisture absorption, ripening inhibition	Starch-lemon film: +8 days shelf life (Fraunhofer IVV, 2024)

4.2. Antioxidant and Oxygen Scavenger Systems

In the context of meat, lipid oxidation represents a critical determinant of quality deterioration, as it results in the synthesis of undesirable compounds, notably malondialdehyde (MDA). Active packaging mitigates this phenomenon by either liberating antioxidant substances or sequestering surplus oxygen (Lee *et al.*, 2018). Frequently utilized antioxidant agents in this form of packaging encompass vitamin E, rosemary extract, natural polyphenols, and metallic adsorbents such as iron powder (Jin *et al.*, 2025).

For instance, whey protein films incorporating rosemary extract on salami successfully maintained malondialdehyde and hexanal concentrations below 0.5 mg/kg over a 90-day storage period at 5°C, thereby demonstrating enhanced oxidative stability compared to traditional packaging methods (Zhang *et al.*, 2025). Recent innovations encompass the application of nanomaterials, such as titanium dioxide, within chitosan films to enhance photocatalytic activity, which consequently mitigated oxidation in poultry meat and prolonged shelf life by as much as 7 days. One prominent active packaging technology, Modified Atmosphere Packaging (MAP), serves as a contaminant barrier and selectively inhibits spoilage microorganisms, thereby extending food shelf life (Mohebi and Marquez, 2014).

4.3. Humidity and Ethylene Control Systems

Maintaining humidity levels within the packaging is essential to avoid mold formation and alterations in texture. Bio-based films like starch-lemon, which possess moisture-absorbing capabilities, have demonstrated the ability to extend the shelf life of meat products by approximately 8 days (Fronfer IV, 2024). A new generation of modified starch-based moisture absorbers has proven to be around 2.5 times more effective than silica gel absorbers, highlighting the effectiveness of biodegradable materials in eco-friendly packaging solutions (Mundak, 2024). In addition, active ethylene-absorbing films reduce the rate of spoilage and maintain the color and freshness of the product. (Khodaei *et al.* 2023).

5. Materials and Manufacturing Technologies

Active and intelligent packaging is fabricated from a diverse array of materials, frequently comprising natural or synthetic polymers that incorporate active agents (such as antimicrobials or antioxidants) or exhibit intelligent functionalities (such as sensors). Such materials are required to exhibit characteristics including biodegradability, food safety, and economic viability (Jiang et al., 2023). Recent literature indicates that foundational materials encompass biopolymers (including chitosan, gelatin, starch, and polylactic acid or PLA) and nanomaterials (such as nano silver, zinc oxide or ZnO, and titanium oxide or TiO2) sourced from natural origins or agricultural by-products to promote environmental sustainability (Ahari and Soufiani, 2021). Furthermore, synthetic polymers like polyvinyl alcohol (PVA) and polyhydroxyalkanoates (PHA) are employed to enhance mechanical and sensory characteristics (Biji *et al.*, 2015).

6. Types of Materials Utilized

Biopolymers and Bio-based Materials: These substances are obtained from renewable sources such as food by-products (like fruit peels, shrimp shells, or plant residues) and encompass chitosan (derived from chitin in crustacean shells), gelatin (originating from animal proteins), starch (extracted from corn or potatoes), cellulose (from plant sources), and Poly Lactic Acid (produced from lactic acid fermentation). These materials are biodegradable and can integrate active agents such as anthocyanins (extracted from red cabbage or black rice as pH indicators) or plant essential oils (such as lemon oil or curcumin) to impart antimicrobial or antioxidant attributes (Mkhari et al., 2025). For instance, chitosan is utilized in active films to inhibit bacterial growth, such as that of E. coli, owing to its intrinsic antimicrobial properties (facilitated by amino groups) (Puebla-Duarte *et al.*, 2023). Bio-based materials like PHB (polyhydroxybutyrate) are also suitable for intelligent packaging, possessing the capability to respond to environmental cues (such as temperature or humidity) (Ahari and Soufiani, 2021).

Nanomaterials: Metallic nanoparticles such as nanosilver (noted for potent antibacterial properties in fruits and vegetables) or ZnO and TiO2 (utilized for ethylene and moisture regulation in perishable items) are incorporated to enhance barrier and sensing functionalities. For example, cellulose nanocrystals (CNCs) derived from plant biomass are employed to create oxygen barriers within films (Jiang *et al.*, 2023). Nanocomposites such as nanoclay (to augment barrier properties in beer packaging) or halloysite nanotubes (for ethylene absorption in tomatoes) are also prevalent (Biji *et al.*, 2015).

Smart and Hybrid Polymers: Stimuli-responsive polymers like PNIPAAm (N-isopropylacrylamide) for controlled release contingent upon temperature (with a critical temperature below 32°C) or conductive polymers such as PEDOT: PSS for gas sensing applications are utilized. Hybrid formulations, including chitosan-starch or PLA-PEO for moisture indicators (exhibiting color change at humidity levels exceeding 60%), have been innovated (Mkhari *et al.*, 2025).

7. Manufacturing Methods

Electrospinning: This technique is used to produce nanofibers, enabling the inclusion of active components like curcumin in PVA fibers for prolonged release. Recently, it has been applied to create smart films that contain antimicrobial nanostructures, such as those made from PLA/PEO combined with phycocyanin to serve as pH indicators (Ahari and Soufiani, 2021; Mkhari *et al.*, 2025).

Extrusion and Molding: This industrial approach supports large-scale production of films, such as the extrusion of LDPE with curcumin or PLA mixed with -tocopherol for oxygen absorption. It enhances barrier properties by integrating nanocomposites like starch-clay (Biji *et al.*, 2015; Jiang *et al.*, 2023).

Solvent Casting: A simple, laboratory-scale method for producing thin films involves combining gelatin with anthocyanins and drying the mixture to create indicators for meat freshness. This approach is also effective for incorporating natural extracts such as essential oils (Puebla-Duarte *et al.*, 2023).

3D Printing: This modern technology allows for the creation of intricate structures, including chitosan-anthocyanin films for pork quality indicators and hydrogel-oleogel bigels containing anthocyanins to detect volatile amines. It offers excellent scalability and customization of properties (Mkhari *et al.*, 2025; Ahari and Soufiani, 2021).

Nanotechnology Integration: This encompasses methods like nano-coating (for example, applying nano silver to gelatin films) or encapsulation (such as using magnetic silica nanoparticles for turmeric oil) to enable controlled release. Techniques such as thin film deposition or solvent-based chemistry are utilized in sensor development (Puebla-Duarte *et al.*, 2023). These innovative technologies, which focus on sustainable materials and methods, hold great promise for reducing food waste. Nonetheless, challenges like production costs and the scalability of these processes in industry still need to be addressed (Biji *et al.*, 2015).

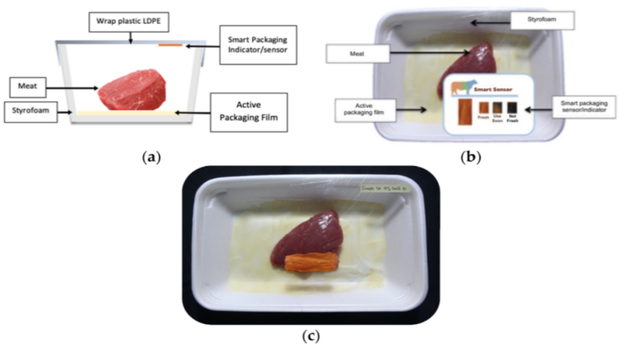

Fig. 1. "Design of a smart and active packaging system (a), prototype of smart packaging (b), and its application on fresh beef (c)." (Dirpan et al., 2022).

8. Smart Packaging: Real Quality Monitoring

Smart packaging offers immediate information concerning the status of food without needing to open the package, utilizing sensors and indicators. These technologies enhance quality, safety, and streamline the supply chain. The importance of monitoring or assessing food quality from production to consumption has grown due to increasing consumer satisfaction, minimizing food waste, and preventing foodborne illnesses (Mohebi and Marquez, 2014). In the present day, food packaging not only protects food from contamination and aids in distribution but can also monitor food from the manufacturing stage until it reaches consumers.

Smart packaging can be viewed as a system capable of executing intelligent tasks such as sensing, detecting, tracking, recording, and communicating, facilitating decisions to extend shelf life, improve quality, enhance safety, provide information, and alert about possible issues. Smart packaging systems comprise data carriers, indicators, and sensors. Indicators deliver visual cues that reflect the internal condition of food items. Digital sensors monitor alterations in the product through the use of transducers (koneti *et al.*, 2023).

9. Types of Smart Packaging

9.1. Time-Temperature Indicators (TTI)

TTIs reflect cumulative temperature variations through a permanent color change. This process is driven by lipid hydrolysis or enzymatic activity. In meat products, TTI based on lipase activity forecasts microbial development in chilled meat packaging, thereby extending the product's shelf life by mitigating temperature abuse. Research demonstrates a strong correlation (R=0.98) with microbial growth in meat. Time-temperature indicators (TTIs) have become vital instruments for thorough quality monitoring within meat supply chains, furnishing essential real-time information that influences various facets of food management, including quality assurance, consumer confidence, and compliance with regulations (Zhang *et al.*, 2025).

Furthermore, temperature monitoring indicators (TTIs) are classified into three groups based on their performance: critical temperature indicators (which identify exposure to temperatures that exceed or fall below a specified threshold), integrated temperature/time indicators or partial history indicators (which detect temperature mismanagement affecting quality), and integrated time-temperature indicators or full history indicators (which track the complete temperature history and identify abuse). TTIs operate based on various principles, including chemical types (like polymerization-based, photochromic, and oxidation reactions), physical mechanisms (such as diffusion, nanoparticles, and electronics), enzymatic types (e.g., hydrolysis using enzymes such as lipase), biological methods (like yeast and lactic acid bacteria), changes in photonic networks, and combinations of polymers and thermal dyes (Abekoon *et al.*, 2024). As an illustration, enzymatic TTIs induce pH shifts via the hydrolysis of lipid substrates, resulting in a color transition (for example, from green to orange/red), and this process is linked to microbial proliferation (Zhang *et al.*, 2025).

The functioning of TTIs involves irreversible changes influenced by time and temperature through mechanisms such as chemical, mechanical, electrochemical, enzymatic, or microbiological activities that result in observable effects, including color shifts, color movement, or physical deformation. For example, polymerization-based TTIs utilize the solid-state polymerization of monomers featuring acetylene groups; photochromic TTIs depend on the thermal fading of photochromic compounds for color alteration; and oxidation reaction-based TTIs are grounded in redox reactions with oxygen (Abekoon *et al.*, 2024). In meat-related applications, nanoparticle TTIs, utilizing silver (AgNPs) and gold (AuNPs) nanodispersions within 3D-printed plant resin containers, identify cumulative temperature fluctuations through colorimetric alterations; for instance, AgNPs above 22°C produce a yellow-green color shift due to an increase in nanoparticle concentration, whereas AuNPs below 4°C result in a red-purple color change through aggregation (cryoagglomeration) (Alcañiz *et al.*, 2025). These mechanisms are effective for monitoring the cold chain in perishable items such as meat and can extend shelf life by curbing microbial growth. In meat and seafood products, temperature time indicators (TTIs) like the OnVu^{TM} system are utilized to estimate color changes in cold meat and to monitor the shelf life of ready-to-eat cold-smoked items, which are linked to microbial growth (Zhang *et al.*, 2025). Recent developments feature enzymatic TTIs that evaluate the freshness of fish by measuring pH alterations resulting from lipid breakdown, thereby minimizing safety hazards (Zhang *et al.*, 2025). The benefits of TTIs encompass enhanced management of the cold chain, reduction of waste by indicating spoilage risks, and increased consumer satisfaction by offering storage details. These external indicators facilitate prompt decision-making and can be integrated with intelligent packaging systems for tracking and HACCP protocols (Abekoon *et al.*, 2024). However, there are drawbacks such as their exclusive focus on temperature (neglecting factors like humidity or oxygen), the irreversibility of many TTIs, and the high costs associated with small producers (Zhang *et al.*, 2025).

9.2. Gas and pH Sensors

These sensors identify volatile substances, including amines (TVB-N), CO2, and H2S. The detection methods involve either electrochemical reactions or color changes. Anthocyanin-agar films can detect putrescine in pork with a sensitivity range of 1-5 ppm and a response time of 2-5 minutes, allowing for an extension of shelf life up to 72 hours. Recent advancements feature titanium dioxide-polyaniline sensors capable of detecting ammonia in pork, showing a response of 0.82 at a concentration of 100 ppm. Odor is a crucial factor in determining the freshness of meat. Each type of meat has distinct characteristics of volatile compounds, resulting in a unique smell for every product. Research has indicated that biogenic amines like tyramine, tryptamine, putrescine, and cadaverine have significant correlations with traditional quality indicators such as total bacterial count, pH, and TVBN in meat products (Mohebi and Marquez, 2014).

9.3. RFID and IoT Systems

RFID technology enables real-time monitoring and is combined with sensors to forecast freshness. In the case of pork, utilizing passive RFID along with machine learning achieves a freshness prediction accuracy of 96.9%. As an essential information technology in food packaging, radio frequency identification (RFID) technology encodes extensive product details on microchips, which include the product name, ingredients, functional attributes, origin, shelf life, weight, price, and usage instructions (Zhang *et al.*, 2025).

9.4. Integration of Active and Intelligent Packaging

Hybrid systems like chitosan films that incorporate color indicators and antimicrobial substances can simultaneously monitor and preserve food. This combination enhances the shelf life of chicken meat by an additional 6 days. The findings indicated that smart packaging provides various benefits compared to conventional packaging, including antimicrobial properties, antioxidant effects, and prolonged shelf life, particularly in industrial processing settings (Khodai *et al.*, 2023).

10. Application in Meat Products

10.1. Case Studies

Red meat shelf life was extended by 6 days using chitosan films with eugenol for chicken, which reduced microbial counts. Gelatin coatings with nisin inhibited Listeria in processed beef, extending shelf life up to 10 days. Nanoparticle H2S sensors accurately detected spoilage in poultry and seafood. Meat products' (poultry, red meat, and seafood) short shelf life is due to spoilage and oxidation from microbial activity and metabolic/enzymatic processes (Sani *et al.*, 2024).

10.2. Effects on Shelf Life

These innovations enhance shelf life by 20-50% by decreasing waste and boosting safety. For instance, with pork, active systems manage TBARS levels and prolong shelf life from 5 to 12 days. As a result, these systems have been utilized to enhance the shelf life and texture of meat and meat products. It is essential to monitor the amount of smart ingredients included in the packaging, as they significantly influence the quality, nutritional characteristics, and overall cost of food items (Khodai *et al.*, 2023).

10.3. Challenges and Future Outlook

The outlook for advanced and intelligent packaging technologies in meat products is certainly encouraging, yet it faces several challenges that necessitate creative solutions and strategic funding. A key obstacle is the elevated cost associated with manufacturing and deploying these systems, which might hinder widespread acceptance in developing nations. Furthermore, concerns regarding the migration of active substances (like nanoparticles or chemical agents) into food necessitate thorough safety evaluations and stringent regulations from bodies such as the FDA and EFSA to guarantee that these technologies remain safe for health. Another significant challenge is environmental sustainability, as many existing materials are derived from non-biodegradable plastics, contributing to ecological pollution. Transitioning from laboratory development to full-scale industrial production also presents obstacles, including issues with scalability, the consistency of performance, and reliability, all of which demand considerable investments in state-of-the-art equipment and refined processes (Sani *et al.*, 2024).

The future of this sector is brimming with new advancements. By incorporating artificial intelligence (AI) and machine learning into intelligent systems, more precise predictions regarding spoilage can be made; for instance, AI algorithms can evaluate sensor data and provide early warnings, potentially extending shelf life by as much as 50%. The emergence of innovative biodegradable materials, like starch-based biopolymers or chitosan enhanced with natural nanomaterials, will promote eco-friendly and sustainable packaging while assisting in minimizing environmental impacts.

Table 3
Types of smart packaging.

Type	Mechanism	Application in meat
Time-temperature indicator (TTI)	Enzymatic/chemical color change	Microbial growth prediction (R^2=0.98) (Zhang *et al.*, 2025)
Gas/pH sensor	Color/electrical change S against amines, CO2, H2S	Detection of putrescine in pork (sensitivity 1-5 ppm)
RFID + IoT	Digital tracking + ML prediction	96.9% accuracy in freshness prediction (Sani *et al.*, 2024)

Next-generation technologies will include stimuli-responsive systems that react to environmental alterations such as temperature or pH, boosting efficiency. Moreover, marrying the Internet of Things (IoT) with RFID technology can completely digitize the supply chain, facilitating traceability from farm to table, which not only enhances safety but also aids in decreasing global waste. The rising adoption of these technologies—projected to grow annually at over 10% until 2030—suggests significant commercialization potential, particularly in developing regions like Asia and the Middle East. Future studies should emphasize international partnerships, comprehensive field testing, and the establishment of global standards, so these innovations can become standard instruments within the meat industry and support worldwide objectives like food security and sustainability (Hidayat *et al.*, 2025; Zhang *et al.*, 2025).

11. Conclusion

Active and intelligent packaging solutions, representing significant advancements in the food sector, have resulted in a remarkable change in how meat products are preserved and their shelf life is extended. By employing sophisticated methods like the controlled release of antimicrobial and antioxidant substances, absorption of oxygen and moisture, and real-time monitoring of quality metrics such as pH, volatile gases, and temperature fluctuations, these systems effectively address conventional issues like microbial spoilage, lipid oxidation, and the deterioration of sensory qualities. Research highlighted in this article indicates that the use of these technologies across various meat products—from fresh red meat and poultry to processed items like sausages and hamburgers—has led to shelf life enhancements of 20 to 100 percent. This not only significantly curtails food waste (as reported by the FAO, over 20 percent of meat production ends up wasted each year) but also enhances food safety and reduces health hazards linked to pathogens such as Salmonella and Listeria. The combination of natural materials, including plant extracts like rosemary and thymol, with nanotechnology has not only bolstered the effectiveness of these systems but also advanced environmental sustainability, since many of these materials are biodegradable and serve as viable alternatives to traditional plastics.

Additionally, intelligent packaging incorporating tools like time-temperature indicators (TTI), gas sensors, and RFID systems facilitates real-time observation of the supply chain and empowers consumers to make better-informed choices. The analyzed case studies indicate that these technologies not only increase the shelf life of products (for instance, extending it from 5 to 12 days in pork) but also assist in lowering production costs while enhancing consumer satisfaction by offering clear information about product freshness and safety. Ultimately, these results highlight that active and smart packaging has transformed from a merely experimental idea or futuristic concept into a strategic and practical approach that is primed for broad implementation within the food sector. These innovations can enhance the competitiveness of meat products in the global marketplace, reduce waste, and aid in achieving sustainable development goals, such as minimizing food waste by 2030. Nonetheless, the overall effectiveness of these systems hinges on addressing current challenges and prioritizing applied research to ensure these technologies become an essential component of the food supply chain (Hidayat *et al.*, 2024).

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