



Advances and functional perspectives on next-generation edible films and coatings for meat products

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ABSTRACT

Edible films and coatings (EFCs) are emerging as sustainable alternatives to conventional meat packaging. Composed of plant- and animal-based biopolymers, they act as barriers to oxygen and moisture while providing active protection when combined with natural antioxidants and antimicrobials. Advances in single-layer, multilayer, and Layer-by-Layer (LbL) systems have improved their mechanical strength, barrier performance, and controlled release capabilities. The integration of plant extracts, essential oils, and polyphenols enhances oxidative stability, inhibits microbial growth, and maintains meat quality. Hybrid structures combining plant and animal materials further extend shelf life under refrigeration. With their bioactive and innovative designs, EFCs offer effective solutions for meat preservation and environmental sustainability.

1. Introduction

The demand for sustainable, clean-label, and high-quality meat products has accelerated research into edible films and coatings (EFCs) as eco-friendly packaging solutions. Conventional petroleum-based packaging, while offering good barrier and mechanical properties, contributes to environmental pollution and micro plastic accumulation due to its non-biodegradability (Gheorghita *et al.*, 2020; Bremenkamp, 2025). Biodegradable films and coatings derived from renewable resources, on the other hand, provide both protective barriers and bioactivity, especially when formulated with natural antioxidants and antimicrobials (Vilca *et al.*, 2023; Stoleru *et al.*, 2024). Studies have shown that these systems can effectively reduce oxidative rancidity and microbial spoilage, thereby extending the

shelf life and quality of meat products while aligning with sustainability goals (Umaraw *et al.*, 2020; Sayadi *et al.*, 2022; Smaoui *et al.*, 2022; Fatima *et al.*, 2024).

Although the terms “film” and “coating” are sometimes used interchangeably, they differ in structure and application. Edible films are pre-formed thin layers, typically manufactured by casting or extrusion, and can be applied as standalone sheets around meat products to improve oxygen and moisture barrier performance (Suhag *et al.*, 2020). In contrast, edible coatings are applied directly to the surface of meat by dipping, spraying, or brushing, creating a continuous and integrated layer that adheres tightly to the product matrix (Ansrade *et al.*, 2012; Umaraw *et al.*, 2020). Coatings are particularly advantageous for incorporating bioactive

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compounds, such as clove oil, argan oil, lemongrass oil, apple peel, post-biotics, or polyphenolic plant extracts, enabling active protection against oxidation and microbial growth (Shin et al., 2017; Stoleru et al., 2021; Abbasi et al., 2023; Jafari et al., 2025). The functionality of EFCs depends on both raw material composition and structural design. Plant-based biopolymers (e.g., starch, pectin, cellulose, zein) provide excellent film-forming ability and gas barrier properties, whereas animal-derived polymers (e.g., gelatin, whey protein isolate (WPI), casein) exhibit superior oxygen barrier and mechanical performance (Azeredo et al., 2022). Hybrid systems, such as WPI combined with carnauba wax or gelatin-zein composites, combine these advantages and significantly enhance oxidative stability (Kandasamy et al., 2021; Pires et al., 2024). Structurally, EFCs are classified into single-layer, multilayer, and Layer-by-Layer (LbL) systems (Xiao et al., 2016). While single-layer films are simple but often require additives to improve barrier properties, multilayer structures—typically composed of protein and lipid layers—provide superior control over moisture and oxygen transmission (Wang et al., 2022; Grzebieniarz et al., 2023; Dargahi et al., 2024; Kiattijiranon et al., 2024). Advanced LbL coatings, created through sequential deposition of oppositely charged polymers, allow precise thickness control and controlled release of bioactive compounds (Siddiqui et al., 2023; Jurić et al., 2023). EFCs play a crucial role in maintaining the quality attributes of meat by extending shelf life, preserving color stability, reducing lipid and protein oxidation, and enhancing sensory characteristics (Sánchez-Ortega et al., 2014; Sharma & Jambhulkar et al., 2014). Antioxidant-enriched films have been shown to reduce thiobarbituric acid reactive substances (TBARS) by 30–50%, while coatings with essential oils or polyphenolic compounds inhibit microbial spoilage and improve consumer acceptability (Ansarian et al., 2021; Xue et al., 2021; Bai et al., 2022; Smaoui et al., 2022). This review aims to provide a comprehensive overview of plant- and animal-based biopolymers, structural approaches, such as single-layer, multilayer, and LbL systems, and the integration of functional additives, while discussing current advancements and

future perspectives for next-generation EFCs that align with sustainability and clean-label requirements.

2. Structural types of edible films and coatings

The structure of EFCs strongly affects barrier capacity, mechanical strength, flexibility, and bioactive release (Moeini et al., 2022). Polymer arrangement, lipid/protein layers, and additive distribution influence food protection (Gómez-Estaca et al., 2023). Accordingly, EFCs can be tailored to reduce oxygen permeability, delay spoilage, and improve sensory quality of meat products (Alias et al., 2022; Karnwal et al., 2025). EFCs are classified as single-layer, multilayer, or layer-by-layer (LbL) systems, each with distinct benefits. Single-layer films, based on polysaccharides, proteins, or lipids, are simple and economical, but often show weak water vapor resistance (Jamroz et al., 2019; Lopes et al., 2020; Agarwal et al., 2021; Bashkar et al., 2023; Grzebieniarz et al., 2023). Incorporating active compounds, like essential oils or antioxidants, improves their performance, as shown with starch films containing oregano (Shen et al., 2022) or chitosan with rosemary oil (Farokhzad et al., 2023). Multilayer films, combining complementary layers, such as protein for oxygen barrier and lipid for moisture resistance, achieve superior protective effects (Alias et al., 2022; Jiang et al., 2022). They significantly reduce water vapor transmission and enhance oxidative stability in meat (Anukiruthika et al., 2020; Xie, 2023), and are widely used for fresh cuts, sausages, and ready-to-eat products. LbL coatings, based on sequential deposition of oppositely charged polymers (e.g., chitosan/pectin), create nanostructured films with tunable thickness and controlled release (Yang et al., 2019; Andrade et al., 2021; Hernandez-Garcia et al., 2022; Cai et al., 2023). When enriched with essential oils or phenolic extracts, they inhibit microbes and delay oxidation (Vital et al., 2016; Langroodi et al., 2021; He & Wang, 2022; Antonino et al., 2023). Nano emulsions and nano cellulose further enhance stability, transparency, and barrier capacity, enabling extended preservation of meat and seafood (Kim et al., 2018; Zhang et al., 2024; Khorami et al., 2024).

3. Integrated biopolymer systems and functional additives for meat preservation

EFCs are primarily developed from plant-based and animal-based biopolymers, which serve as the main structural matrices and determine their functional performance. Plant-derived materials are widely used in EFCs due to their renewability, biodegradability, and excellent film-forming abilities. Polysaccharides, such as starch, pectin, cellulose derivatives (e.g., carboxymethyl cellulose, hydroxypropyl methylcellulose), and alginate, are known for their strong oxygen barrier properties (Díaz-Montes & Castro-Muñoz, 2021). Due to their hydrophilic nature, these matrices are often combined with lipid components, like carnauba and candelilla wax or essential oils, to enhance moisture resistance (Devi *et al.*, 2024). Plant proteins, including soy protein isolate, zein, pea protein, and pumpkin seed protein, contribute mechanical strength, flexibility, and transparency, making them ideal for edible film formation (Khwaldia *et al.*, 2024). In addition to structural roles, plant-based matrices are frequently functionalized with natural bioactive compounds to improve oxidative and microbial stability. Natural antioxidants, such as grape seed extract, green tea catechins, rosemary, and pomegranate peel extract, are incorporated to scavenge free radicals and inhibit lipid oxidation (Xie *et al.*, 2023). For example, starch-based films enriched with oregano essential oils have significantly delayed oxidative rancidity and color deterioration in fish fillets (Martins *et al.*, 2021). Similarly, natural antimicrobials like thyme, oregano, cinnamon, and clove essential oils—rich in phenolic compounds such as carvacrol and thymol—have been shown to effectively reduce spoilage and pathogenic microorganisms (Antonino *et al.*, 2024). Also, starch-based films with oregano oil, for instance, have achieved a 50% reduction in total coliform counts on beef during storage (Cestari *et al.*, 2021).

Animal-derived biopolymers, including gelatin, whey protein isolate (WPI), casein, collagen, and egg albumin, are valued for their superior mechanical properties and oxygen barrier performance (Benbettaieb *et al.*, 2016; Rahman *et al.*, 2023). These polymers can form strong, transparent films, and when combined with lipid components such as beeswax or milk fat derivatives, they provide enhanced water vapor resistance (Castro-Rosas *et al.*, 2016; Devi *et al.*, 2022). Animal-based films are also highly compatible with bioactive

additives. Enrichment with natural antioxidants, like rosemary, elderberry, guava leaf, shallot, and green tea, can significantly reduce lipid oxidation and maintain the desirable red color of meat during storage (Hamann *et al.*, 2022; Lackner *et al.*, 2024; Chang *et al.*, 2023; Velaverde *et al.*, 2024; Yeddes *et al.*, 2025). Hybrid films that combine plant and animal polymers (e.g., gelatin-zein composites or WPI-carnauba wax layers) have demonstrated synergistic effects, improving both barrier properties and active functionalities (Fitriani *et al.*, 2023). For example, gelatin-chitosan-based edible nano emulsion coating incorporating rosemary extract and ϵ -poly-L-lysine (ϵ -PL) has demonstrated superior antimicrobial and antioxidant efficacy for ready-to-eat carbonado chicken. The nano emulsion significantly reduced total viable bacterial counts, TBARS values, and pH variation over 16 days of refrigerated storage, thereby extending shelf life by at least 6 days compared to uncoated samples and coarse emulsions (Zhao *et al.*, 2024). Advanced Layer-by-Layer (LbL) coatings, formed through the sequential electrostatic deposition of oppositely charged biopolymers, such as chitosan and alginate, have demonstrated enhanced preservation effects when loaded with natural bioactive agents. Recent studies have shown that bilayer systems incorporating fucoidan from *Sargassum angustifolium*, grapefruit seed extract, or combinations of tannic acid and cinnamaldehyde nano emulsions not only extend the shelf life of fish and shrimp products significantly (up to 16 days) but also provide strong antimicrobial action, lipid oxidation inhibition, and even real-time freshness monitoring through pH-sensitive layers (Kim *et al.*, 2018; Khorami *et al.*, 2024; Wu *et al.*, 2024). EFCs not only delay lipid and protein oxidation but also inhibit spoilage and pathogenic microorganisms, thereby extending shelf life and preserving desirable sensory attributes (Table 1). Another important function of EFCs is moisture retention and texture preservation, as they minimize water loss and prevent toughening during cold storage (Umaraw *et al.*, 2020; Karnwal *et al.*, 2025). Hybrid biopolymer films (e.g., gelatin-zein or WPI-carnauba wax composites) ensure juicier and more tender meat over time (Arcan & Yemenicioğlu, 2013; Zhang *et al.*, 2018; Cheng *et al.*, 2022; Hu *et al.*, 2023). Sensory evaluations further confirm that natural bioactives such as rosemary extract or green tea polyphenols enhance flavor stability and consumer acceptability (Sharma *et al.*, 2021).

Table 1. Summary of Edible Films and Coatings for Meat Preservation

Film/Coating Type	Active Compounds	Main Application	Key Results	References
Alginate coatings	Essential oils	Fresh meat	Inhibited microbial spoilage; reduced weight loss	<i>Gheorghita et al.</i> , 2020
Edible alginate films with pineapple peel extract	Phenolic antioxidants	Beef	Antioxidant protection; oxidative stability maintained	<i>Lourenço et al.</i> , 2020
Chitosan film with oregano & thyme essential oil	Oregano & thyme essential oil	Beef	Antimicrobial effect; improved oxidative stability	<i>Gaba et al.</i> , 2022
Antimicrobial/antioxidant coatings	Natural extracts	Chicken meat	Improved shelf life & safety	<i>Moura-Alves et al.</i> , 2023
Polysaccharide-based coatings	Essential oils, bioactive nanosystems	Meat & fish	Antimicrobial and antioxidant effects	<i>Hashemi et al.</i> , 2023
Fish gelatin-pectin coatings	Lemongrass essential oil	Chicken meat	Antimicrobial and sensory improvement	<i>Carraro et al.</i> , 2023
Gelatin/carboxymethyl chitosan/guar gum coatings	Shallot waste extracts	Beef	Reduced microbial load; safety improvement	<i>Nguyen et al.</i> , 2023
Ethyl cellulose/gelatin-carboxymethyl chitosan bilayer film	Euryale ferox polyphenols	Cooked meat	Antioxidant and antimicrobial effect	<i>Cai et al.</i> , 2023
Composite coatings	Nanocellulose + chitosan	Meat	Barrier enhancement; antimicrobial and antioxidant activity	<i>Costa et al.</i> , 2021
pH-sensitive bilayer film (smart packaging)	Tannic acid–cinnamaldehyde nanoemulsion + alizarin	Shrimp	UV protection, antimicrobial effect, pH monitoring, freshness indicator	<i>Wu et al.</i> , 2024
Graphene oxide multilayer films	Graphene oxide + chitosan + poly(l-lactic acid-poly butylene itaconate copolymers	Chilled meat	High barrier properties, low O ₂ permeability, delayed spoilage	<i>Zhang et al.</i> , 2024
Curcumin-loaded chitosan/egg yolk film	Curcumin	Pork	Freshness preservation; antioxidant activity	<i>Jiang et al.</i> , 2024
Olive leaf extract coatings	Olive leaf phenolics	Cooked meat	Antioxidant and antimicrobial protection	<i>Şen & Güleç</i> , 2024
Acorn phenolic-rich coatings	Acorn extract	Chicken patties	Improved oxidative stability, sensory quality	<i>Vallejo-Torres et al.</i> , 2024
Chitosan nanocomposites	Biopreservatives, nanoparticles	Meat	Strong antimicrobial and antioxidant properties	<i>Heras et al.</i> , 2024
κ-Carrageenan-based coatings	Resveratrol, quercetin	Goat patties	Antioxidant effect, shelf-life extension	<i>Şengül & Şen</i> , 2025
Alginate-based coatings + irradiation	Myrtle, rosemary extracts	Beef	Strong antioxidant and antimicrobial protection	<i>Smeti et al.</i> , 2025
Sodium alginate coatings + preservatives	Potassium sorbate	Pork	Antimicrobial effect, shelf life extension	<i>Jiang et al.</i> , 2025
Nanocellulose-based coatings	Forsythia essential oil	Fresh meat	Antimicrobial and barrier improvement	<i>Cheng et al.</i> , 2024

4. Conclusion

Edible films and coatings represent a promising pathway toward reducing reliance on conventional plastic packaging in the meat industry, offering protective functionality while supporting clean-label and environmental objectives. By leveraging the complementary properties of plant-derived and animal-derived biopolymers, these systems can be tailored to improve moisture and gas barrier capacity, mechanical integrity, and controlled release of active agents. Advances in multilayer and

LbL structures have expanded the design possibilities, enabling better integration of bioactive components for oxidative and microbial stability. Nevertheless, their broader implementation depends on overcoming economic, technological, and regulatory barriers, as well as ensuring consumer trust. Future developments are expected to focus on intelligent and responsive packaging concepts, integration of by-product valorization strategies, and scalable production technologies, strengthening the role of EFCs in sustainable meat preservation.

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