Content is avaliable at SCOPUS

Meat Technology — Special Issue 66/3

www.meatcon.rs ▪ www.journalmeattechnology.com

UDK: 637.5.058

ID: 179653897

https://doi.org/10.18485/meattech.2025.66.3.3

Review Paper

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

Meltem Serdaroğlu[1*] and *Hülya Serpil Kavuşan*[1]

[1] *Ege University, Engineering Faculty, Food Engineering Department, Izmir, Turkey*

ARTICLE INFO

Keywords:
Edible films
Coatings
Meat preservation
Antioxidants
Antimicrobials
Multilayer films
Layer-by-Layer (LbL) coating

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 preformed 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

***Corresponding author:** Meltem Serdaroğlu, *meltem.serdaroglu@ege.edu.tr*

Paper received August 1st 2025. Paper accepted August 5th 2025.
The paper was presented at the 63rd International Meat Industry Conference "Food for Thought: Innovations in Food and Nutrition" – Zlatibor, October 05th-08th 2025.
Published by Institute of Meat Hygiene and Technology – Belgrade, Serbia.

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

Disclosure statement: No potential conflict of interest was reported by the authors.

Funding: This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

Abbasi, A., Sabahi, S., Bazzaz, S., Tajani, A., Lahouty, M., Aslani, R., & Hosseini, H. (2023). An edible coating utilizing *Malva sylvestris* seed polysaccharide mucilage and postbiotic from *Saccharomyces cerevisiae* var. *boulardii* for the preservation of lamb meat. *International Journal of Biological Macromolecules,* 242, 125660. https://doi.org/10.1016/j.ijbiomac.2023.125660

Agarwal, S. (2021). Major factors affecting the characteristics of starch-based biopolymer films. *European Polymer Journal,* 160, 110788. https://doi.org/10.1016/j.eurpolymj.2021.110788

Alias, A., Khairul, W., & Sarbon, N. (2022). Emerging materials and technologies of multi-layer film for food packaging application: A review. *Food Control,* 134, 108875. https://doi.org/10.1016/j.foodcont.2022.108875

Andrade, J., González-Martínez, C., & Chiralt, A. (2021). Antimicrobial PLA-PVA multilayer films containing phenolic compounds. *Food Chemistry,* 375, 131861. https://doi.org/10.1016/j.foodchem.2021.131861

Ansarian, E., Aminzare, M., Azar, H., Mehrasbi, M., & Bimakr, M. (2021). Nanoemulsion-based basil seed gum edible film containing resveratrol and clove essential oil: In vitro antioxidant properties and its effect on oxidative stability and sensory characteristics of camel meat during refrigeration storage. *Meat Science,* 185, 108716. https://doi.org/10.1016/j.meatsci.2021.108716

Antonino, C., Difonzo, G., Faccia, M., & Caponio, F. (2023). Effect of edible coatings and films enriched with plant extracts and essential oils on the preservation of animal-derived foods. *Journal of Food Science,* 88(8), 3659–3674. https://doi.org/10.1111/1750-3841.16894

Antonino, C., Difonzo, G., Faccia, M., & Caponio, F. (2024). Effect of edible coatings and films enriched with plant extracts and essential oils on the preservation of animal-derived foods. *Journal of Food Science,* 89(2), 748–772. https://doi.org/10.1111/1750-3841.16894

Anukiruthika, T., Sethupathy, P., Wilson, A., Kashampur, K., Moses, J. A., & Anandharamakrishnan, C. (2020). Multilayer packaging: Advances in preparation techniques and emerging food applications. *Comprehensive Reviews in Food Science and Food Safety,* 19(3), 1156–1186. https://doi.org/10.1111/1541-4337.12547

Arcan, I., & Yemenicioğlu, A. (2013). Development of flexible zein–wax composite and zein–fatty acid blend films for controlled release of lysozyme. *Food Research International,* 51(1), 208–216. https://doi.org/10.1016/j.foodres.2012.12.011

Azeredo, H., Otoni, C., & Mattoso, L. (2022). Edible films and coatings – Not just packaging materials. *Current Research in Food Science,* 5, 1590–1595. https://doi.org/10.1016/j.crfs.2022.09.008

Bai, M., Zhou, Q., Zhang, J., Li, T., Cheng, J., Liu, Q., Xu, W., & Zhang, Y. (2022). Antioxidant and antibacterial properties of essential oils-loaded β-cyclodextrin-epichlorohydrin oligomer and chitosan composite films. *Colloids and Surfaces B: Biointerfaces,* 215, 112504. https://doi.org/10.1016/j.colsurfb.2022.112504

Benbettaïeb, N., Gay, J., Karbowiak, T., & Debeaufort, F. (2016). Tuning the functional properties of polysaccharide–protein bio-based edible films by chemical, enzymatic, and physical cross-linking. *Comprehensive Reviews in Food Science and Food Safety,* 15(4), 739–752. https://doi.org/10.1111/1541-4337.12210

Bremenkamp, I., & Gallagher, M. (2025). Edible coatings for ready-to-eat products: Critical review of recent studies, sustainable packaging perspectives, challenges and emerging trends. *Polymers,* 17(5), 1218. https://doi.org/10.3390/polym17051218

Cai, M., Zhang, X., Zhong, H., Li, C., Shi, C., Cui, H., & Lin, L. (2023). Ethyl cellulose/gelatin–carboxymethyl chitosan bilayer films doped with *Euryale ferox* seed shell polyphenol for cooked meat preservation. *International Journal of Biological Macromolecules,* 247, 128286. https://doi.org/10.1016/j.ijbiomac.2023.128286

Carraro, M., Djellali, S., Azizah, F., Nursakti, H., & Ningrum, A. (2023). Development of edible composite film from fish gelatin–pectin incorporated with lemongrass essential oil and its application in chicken meat. *Polymers,* 15(9), 2075. https://doi.org/10.3390/polym15092075

Castro-Rosas, J., Cruz-Galvez, A., Gómez-Aldapa, C., Falfán-Cortés, R., Guzmán-Ortiz, F., & Rodríguez-Marín, M. (2016). Biopolymer films and the effects of added lipids, nanoparticles and antimicrobials on their mechanical and barrier properties: A review. *International Journal of Food Science and Technology,* 51(9), 1967–1978. https://doi.org/10.1111/ijfs.13183

Cestari, L. A., da Silva Scapim, M. R., Madrona, G. S., Yamashita, F., Biondo, P. B. F., Carvalho, V. M., & do Prado, I. N. (2021). Production, antioxidant characterization and application of active starch-based films containing essential oils for beef packaging. *Research, Society and Development,* 10(8), e4310816903. https://doi.org/10.33448/rsd-v10i8.16903

Chang, Y., Choi, J., Lee, J., & Han, J. (2023). Development of gelatin–sodium caseinate high-oxygen-barrier film containing elderberry (*Sambucus nigra* L.) extract and its antioxidant capacity on pork. *SSRN Electronic Journal.* https://doi.org/10.2139/ssrn.4359046

Cheng, Y., Zhai, X., Wu, Y., Li, C., Zhang, R., Sun, C., Wang, W., & Hou, H. (2022). Effects of natural wax types on the physicochemical properties of starch/gelatin edible films fabricated by extrusion blowing. *Food Chemistry,* 401, 134081. https://doi.org/10.1016/j.foodchem.2022.134081

Costa, S., Ferreira, D., Teixeira, P., Ballesteros, L., Teixeira, J., & Fangueiro, R. (2021). Active natural-based films for food packaging applications: The combined effect of chitosan and nanocellulose. *International Journal of Biological Macromolecules,* 183, 1270–1279. https://doi.org/10.1016/j.ijbiomac.2021.02.105

Dargahi, A., Runka, J., Hammami, A., & Naguib, H. (2024). High-temperature multilayer composite films of polyethylene/ethylene vinyl alcohol with enhanced flexural moduli and gas barrier properties. *ACS Applied Polymer Materials,* 6(2), 679–689. https://doi.org/10.1021/acsapm.4c01666

Devi, L., Jaiswal, A., & Jaiswal, S. (2024). Lipid incorporated biopolymer-based edible films and coatings in food packaging: A review. *Current Research in Food Science, 8*, 100720. https://doi.org/10.1016/j.crfs.2024.100720

Díaz-Montes, E., & Castro-Muñoz, R. (2021). Edible films and coatings as food-quality preservers: An overview. *Foods,* 10(2), 249. https://doi.org/10.3390/foods10020249

Farokhzad, P., Dastgerdi, A. A., & Nimavard, J. T. (2023). The effect of chitosan and rosemary essential oil on the quality characteristics of chicken burgers during storage. *Journal of Food Processing and Preservation,* 47(1), e8381828. https://doi.org/10.1111/jfpp.8381828

Fatima, M., Mir, S., Ali, M., Hassan, S., Khan, Z., & Waqar, K. (2024). Synthesis and applications of chitosan derivatives in food preservation: A review. *European Polymer Journal,* 199, 113242. https://doi.org/10.1016/j.eurpolymj.2024.113242

Fitriani, F., Bilad, M., Aprilia, S., & Arahman, N. (2023). Biodegradable hybrid polymer film for packaging: A review. *Journal of Natural Fibers,* 20(1), 2159606. https://doi.org/10.1080/15440478.2022.2159606

Gaba, A., El-Tawab, A., Abdelmonem, M., & Morsy, M. (2022). Protective impact of chitosan film loaded with oregano and thyme essential oils on the microbial profile and quality attributes of beef meat. *Antibiotics,* 11(5), 583. https://doi.org/10.3390/antibiotics11050583

Gheorghita, R., Gutt, G., & Amariei, S. (2020). The use of edible films based on sodium alginate in meat product packaging: An eco-friendly alternative to conventional plastic materials. *Coatings,* 10(2), 166. https://doi.org/10.3390/coatings10020166

Grzebieniarz, W., Biswas, D., Roy, S., & Jamróz, E. (2023). Advances in biopolymer-based multi-layer film preparations and food packaging applications. *Food Packaging and Shelf Life,* 37, 101033. https://doi.org/10.1016/j.fpsl.2023.101033

Hamann, D., Puton, B., Comin, T., Colet, R., Valduga, E., Zeni, J., Steffens, J., Junges, A., Backes, G., & Cansian, R. (2022). Active edible films based on green tea extract and gelatin for coating of fresh sausage. *Meat Science,* 194, 108966. https://doi.org/10.1016/j.meatsci.2022.108966

He, S., & Wang, Y. (2022). Antimicrobial and antioxidant effects of kappa-carrageenan coatings enriched with cinnamon essential oil in pork meat. *Foods,* 11(18), 2885. https://doi.org/10.3390/foods11182885

Heras, M., Huang, C., Chang, C., & Lu, K. (2024). Trends in chitosan-based films and coatings: A systematic review of incorporated biopreservatives, biological properties, and nanotechnology applications in meat preservation. *Food Packaging and Shelf Life,* 42, 101259. https://doi.org/10.1016/j.fpsl.2024.101259

Hernández-García, E., Vargas, M., & Torres-Giner, S. (2022). Quality and shelf-life stability of pork meat fillets packaged in multilayer polylactide films. *Foods,* 11(3), 426. https://doi.org/10.3390/foods11030426

Hu, L., Zhao, P., Wei, Y., Guo, X., Deng, X., & Zhang, J. (2023). Properties of allicin–zein composite nanoparticle gelatin film and their effects on the quality of cold, fresh beef during storage. *Foods,* 12(19), 3713. https://doi.org/10.3390/foods12193713

Jafari, S., Sourki, A., & Pashangeh, S. (2025). Emulsion electrospinning of lemongrass essential oil-loaded *Ferula haussknechtii* gum/polyethylene oxide as bioactive coating. *Food Hydrocolloids for Health,* 5, 100195. https://doi.org/10.1016/j.fhfh.2025.100195

Jamróz, E., Kulawik, P., & Kopel, P. (2019). The effect of nanofillers on the functional properties of biopolymer-based films: A review. *Polymers,* 11(4), 675. https://doi.org/10.3390/polym11040675

Jiang, J., Watowita, P., Chen, R., Shi, Y., Geng, J., Takahashi, K., Li, L., & Osako, K. (2022). Multilayer gelatin/myofibrillar films containing clove essential oil: Properties, protein–phenolic interactions, and migration of active compounds. *Food Packaging and Shelf Life,* 33, 100842. https://doi.org/10.1016/j.fpsl.2022.100842

Jiang, W., Ding, X., Zhang, Z., Li, W., Li, X., Chen, L., Tang, Y., & Jiang, Y. (2025). Developing sodium alginate-based edible film incorporated with potassium sorbate and application for fresh cold pork preservation. *Food Control,* 152, 111154. https://doi.org/10.1016/j.foodcont.2025.111154

Jiang, Y., Sun, Y., Wei, C., Li, X., Deng, W., Wu, S., Kong, F., & Sheng, L. (2024). Development and characterization of curcumin-loaded chitosan/egg yolk freshness-keeping edible films for chilled fresh pork packaging application. *International Journal of Biological Macromolecules,* 247, 133907. https://doi.org/10.1016/j.ijbiomac.2024.133907

Jurić, S., Bureš, M. S., Vlahoviček-Kahlina, K., Stracenski, K. S., Fruk, G., Jalšenjak, N., & Bandić, L. M. (2023). Chitosan-based layer-by-layer edible coatings application for the preservation of mandarin fruit bioactive compounds and organic acids. *Food Chemistry: X,* 17, 100575. https://doi.org/10.1016/j.fochx.2022.100575

Kandasamy, S., Yoo, J., Yun, J., Kang, H.-B., Seol, K.-H., Kim, H.-W., & Ham, J.-S. (2021). Application of whey protein-based edible films and coatings in food industries: An updated overview. *Coatings,* 11(9), 1056. https://doi.org/10.3390/coatings11091056

Karnwal, A., Kumar, G., Singh, R., Selvaraj, M., Malik, T., & Tawaha, A. (2025). Natural biopolymers in edible coatings: Applications in food preservation. *Food Chemistry:* X(25), 102171. https://doi.org/10.1016/j.fochx.2025.102171

Khorami, F., Babaei, S., Valizadeh, S., Naseri, M., & Golmakani, M. T. (2024). Bilayer coatings for extension of the shelf life of fish fillets: Incorporating seaweed sulfated polysaccharides in chitosan–alginate LbL structures. *Food Science & Nutrition,* 12(4), 2511–2522. https://doi.org/10.1002/fsn3.3818

Khwaldia, K., Hosni, K., & Hassoun, A. (2024). Valorization of by-products from plant ingredients production chain. In *Handbook of Plant-Based Food and Drinks Design* (pp. 427–440). Academic Press. https://doi.org/10.1016/B978-0-323-90944-7.00025-0

Kiattijiranon, P., Auras, R., & Sane, A. (2024). Enhanced functional properties for packaging applications using sodium alginate/starch bilayer and multilayer films. *ACS Applied Polymer Materials,* 6(3), 1355–1365. https://doi.org/10.1021/acsapm.4c00224

Kim, J. H., Hong, W. S., & Oh, S. W. (2018). Effect of layer-by-layer antimicrobial edible coating of alginate and chitosan with grapefruit seed extract for shelf-life extension of shrimp (*Litopenaeus vannamei*) stored at 4 °C. *International Journal of Biological Macromolecules,* 120, 1468–1473. https://doi.org/10.1016/j.ijbiomac.2018.09.039

Langroodi, A., Nematollahi, A., & Sayadi, M. (2021). Chitosan coating incorporated with grape seed extract and *Origanum vulgare* essential oil: An active packaging for turkey meat preservation. *Journal of Food Measurement and Characterization,* 15(4), 2790–2804. https://doi.org/10.1007/s11694-021-00867-0

Lopes, I., Paixão, L., Da Silva, L., Rocha, A., Filho, A., & Santana, A. (2020). Elaboration and characterization of biopolymer films with alginate and babassu coconut mesocarp. *Carbohydrate Polymers,* 234, 115747. https://doi.org/10.1016/j.carbpol.2019.115747

Lourenço, S., Fraqueza, M., Fernandes, M., Moldão-Martins, M., & Alves, V. (2020). Application of edible alginate films with pineapple peel active compounds on beef meat preservation. *Antioxidants,* 9(8), 667. https://doi.org/10.3390/antiox9080667

Martins, P. C., Bagatini, D. C., & Martins, V. G. (2021). Oregano essential oil addition in rice starch films and its effects on the chilled fish storage. *Journal of Food Science and Technology,* 58(4), 1562–1573. https://doi.org/10.1007/s13197-020-04661-y

Moeini, A., Pedram, P., Fattahi, E., Cerruti, P., & Santagata, G. (2022). Edible polymers and secondary bioactive compounds for food packaging applications: Antimicrobial, mechanical, and gas barrier properties. *Polymers,* 14(12), 2395. https://doi.org/10.3390/polym14122395

Moura-Alves, M., Esteves, A., Ciríaco, M., Silva, J., & Saraiva, C. (2023). Antimicrobial and antioxidant edible films and coatings in the shelf-life improvement of chicken meat. *Foods,* 12(12), 2308. https://doi.org/10.3390/foods12122308

Pires, A. F., Díaz, O., Cobos, A., & Pereira, C. D. (2024). A review of recent developments in edible films and coatings: Focus on whey-based materials. *Foods,* 13(16), 2638. https://doi.org/10.3390/foods13162638

Rahman, S., Gogoi, J., Dubey, S., & Chowdhury, D. (2023). Animal-derived biopolymers for food packaging applications: A review. *International Journal of Biological Macromolecules,* 242, 128197. https://doi.org/10.1016/j.ijbiomac.2023.128197

Sánchez-Ortega, I., García-Almendárez, B., Santos-López, E., Amaro-Reyes, A., Barboza-Corona, J., & Regalado, C. (2014). Antimicrobial edible films and coatings for meat and meat products preservation. *The Scientific World Journal,* 2014, 248935. https://doi.org/10.1155/2014/248935

Sayadi, M., Langroodi, A., Amiri, S., & Radi, M. (2022). Effect of nanocomposite alginate-based film incorporated with cumin essential oil and TiO_2 nanoparticles on chemical, microbial, and sensory properties of fresh meat/beef. *Food Science & Nutrition,* 10(5), 1401–1413. https://doi.org/10.1002/fsn3.2724

Sharma, R., Bhat, Z., Kumar, A., Kumar, S., Bhatti, M., & Jayawardena, R. (2021). *Rubia cordifolia*-based novel edible film for improved lipid oxidative and microbial stability of meat products. *Journal of Food Processing and Preservation,* 45(11), e15654. https://doi.org/10.1111/jfpp.15654

Sharma, V., & Jambhulkar, A. (2021). Coating on meat and meat products: A review. *International Journal of Chemical Studies,* 9(2), 2418–2423. https://doi.org/10.22271/chemi.2021.v9.i2ai.12082

Shen, Y., Zhou, J., Yang, C., Chen, Y., Yang, Y., Zhou, C., & Yang, H. (2022). Preparation and characterization of oregano essential oil-loaded *Dioscorea zingiberensis* starch film with antioxidant and antibacterial activity and its application in chicken preservation. *International Journal of Biological Macromolecules,* 212, 20–30. https://doi.org/10.1016/j.ijbiomac.2022.05.031

Shin, S., Chang, Y., Lacroix, M., & Han, J. (2017). Control of microbial growth and lipid oxidation on beef product using an apple peel-based edible coating treatment. *LWT - Food Science and Technology,* 84, 183–188. https://doi.org/10.1016/j.lwt.2017.05.054

Siddiqui, S. A., Singh, S., Bahmid, N. A., Mehany, T., Shyu, D. J., Assadpour, E., & Jafari, S. M. (2023). Release of encapsulated bioactive compounds from active packaging/coating materials and its modeling: A systematic review. *Colloids and Interfaces,* 7(2), 25. https://doi.org/10.3390/colloids7020025

Smaoui, S., Hlima, H., Tavares, L., Ennouri, K., Braiek, O., Mellouli, L., Abdelkafi, S., & Khaneghah, A. (2022). Application of essential oils in meat packaging: A systematic review of recent literature. *Food Control,* 132, 108566. https://doi.org/10.1016/j.foodcont.2021.108566

Smeti, S., Tibaoui, S., Koubaier, H., Lakoud, A., & Atti, N. (2025). Combined effects of alginate-based active edible coatings and irradiation treatment on the quality characteristics of beef meat at 2 °C. *Applied Food Research,* 5, 100743. https://doi.org/10.1016/j.afres.2025.100743

Stoleru, E., Vasile, C., Irimia, A., & Brebu, M. (2021). Towards a bioactive food packaging: Poly(lactic acid) surface functionalized by chitosan coating embedding clove and argan oils. *Molecules,* 26(15), 4500. https://doi.org/10.3390/molecules26154500

Suhag, R., Kumar, N., Petkoska, A., & Upadhyay, A. (2020). Film formation and deposition methods of edible coating on food products: A review. *Food Research International,* 136, 109582. https://doi.org/10.1016/j.foodres.2020.109582

Şen, B., & Güleç, A. (2024). Effect of edible film prepared with plasma-activated water and olive leaf extract (*Olea europaea* L.) as a potential packaging in cooked meat product. *Food Science & Nutrition,* 12(10), 9227–9237. https://doi.org/10.1002/fsn3.4482

Şengül, E., & Şen, D. (2025). Development and characterization of κ-carrageenan-based edible films enriched with resveratrol or quercetin for shelf-life extension of goat meat burger patties. *Journal of Food Science,* 90(5), 2345–2357. https://doi.org/10.1111/1750-3841.70277

Umaraw, P., Munekata, P., Verma, A., Barba, F., Singh, V., Kumar, P., & Lorenzo, J. (2020). Edible films/coating with tailored properties for active packaging of meat, fish and derived products. *Trends in Food Science & Technology,* 98, 10–24. https://doi.org/10.1016/j.tifs.2020.01.032

Vallejo-Torres, C., Estévez, M., Sánchez-Terrón, G., Ventanas, S., & Morcuende, D. (2024). Alginate-based edible coating impregnated with phenolic-rich extract from acorns improves oxidative stability and odor liking in ready-to-eat chicken patties. *Food Science of Animal Resources,* 44(6), 1234–1246. https://doi.org/10.5851/kosfa.2024.e126

Vilca, J., Ortiz-Quispe, B., Apaza-Cusiatau, C., De Jara, E., Quequezana-Bedregal, M., Gutierrez-Oppe, E., & Filho, P. (2023). Evaluation of the barrier and antimicrobial properties of biodegradable films based on potato waste starch containing natural additives. *SN Applied Sciences,* 5(2), 604. https://doi.org/10.1007/s42452-023-05604-4

Vital, A., Guerrero, A., Monteschio, J., Valero, M., Carvalho, C., De Abreu Filho, B., Madrona, G., & Prado, I. (2016). Effect of edible and active coating (with rosemary and oregano essential oils) on beef characteristics and consumer acceptability. *PLoS ONE,* 11(8), e0160535. https://doi.org/10.1371/journal.pone.0160535

Wang, Y., Xu, C., Yu, X., Zhang, H., & Han, M. (2022). Multilayer flexible electronics: Manufacturing approaches and applications. *Materials Today Physics, 27*, 100647. https://doi.org/10.1016/j.mtphys.2022.100647

Wu, G., Su, W., Huo, L., Guo, Q., Wei, J., Zhong, H., & Li, P. (2024). Sodium alginate/chitosan-based intelligent multifunctional bilayer film for shrimp freshness retention and monitoring. *International Journal of Biological Macromolecules,* 277, 133908. https://doi.org/10.1016/j.ijbiomac.2024.133908

Xiao, F., Pagliaro, M., Xu, Y., & Liu, B. (2016). Layer-by-layer assembly of versatile nanoarchitectures with diverse dimensionality: A new perspective for rational construction of multilayer assemblies. *Chemical Society Reviews,* 45(11), 3088–3121. https://doi.org/10.1039/c5cs00781j

Xie, F. (2023). Biopolymer-based multilayer films and coatings for food preservation: An update of the recent development. *Current Food Science and Technology Reports,* 1(1), 1–12. https://doi.org/10.1007/s44197-023-00001-1

Xie, Q., Liu, G., Zhang, Y., Yu, J., Wang, Y., & Ma, X. (2023). Active edible films with plant extracts: An updated review of their types, preparations, reinforcing properties, and applications in muscle foods packaging and preservation. *Critical Reviews in Food Science and Nutrition,* 63(32), 11425–11447. https://doi.org/10.1080/10408398.2022.2051082

Xue, F., Zhao, M., Liu, X., Chu, R., Qiao, Z., Li, C., & Adhikari, B. (2021). Physicochemical properties of chitosan/zein/essential oil emulsion-based active films functionalized by polyphenols. *Future Foods,* 4, 100033. https://doi.org/10.1016/j.fufo.2021.100033

Yang, W., Xie, Y., Jin, J., Liu, H., & Zhang, H. (2019). Development and application of an active plastic multilayer film by coating a plantaricin BM-1 for chilled meat preservation. *Journal of Food Science,* 84(7), 1864–1870. https://doi.org/10.1111/1750-3841.14608

Yeddes, W., Rybak, K., Rebey, I., Pietrzak, D., Adamczak, L., Hammami, M., Wannes, W., Witrowa-Rajchert, D., Tounsi, M., Tixier, A., & Nowacka, M. (2025). Lipid oxidation and barrier properties of the coated freeze-dried chicken meat with gelatin-chitosan film enriched with rosemary (*Rosmarinus officinalis* L.) extract. *Foods,* 14(7), 1127. https://doi.org/10.3390/foods14071127

Zhang, A., Fan, X., Zeng, X., Xu, J., Zhou, C., Xia, Q., & Pan, D. (2024). Enhancing physicochemical, antimicrobial, and release properties of fish skin gelatin films using dual-layer nanoparticles loaded with tea polyphenols/kojic acid for air-dried chicken preservation. *Food Hydrocolloids,* 149, 109580. https://doi.org/10.1016/j.foodhyd.2023.109580

Zhang, J., Guan, B., Zhang, Y., Hu, J., Sun, T., Dong, T., & Yun, X. (2024). Development of high-barrier poly(L-lactic acid)/chitosan/graphene oxide flexible films for meat packaging by layer-by-layer. *Food Bioscience,* 55, 104304. https://doi.org/10.1016/j.fbio.2024.104304

Zhang, Y., Simpson, B., & Dumont, M. (2018). Effect of beeswax and carnauba wax addition on properties of gelatin films: A comparative study. *Food Bioscience,* 25, 91–98. https://doi.org/10.1016/j.fbio.2018.09.011

Authors info

Meltem Serdaroğlu, https://orcid.org/0000-0003-1589-971X
Hülya Serpil Kavuşan, https://orcid.org/0000-0003-2928-8020