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Review Article

Use of whey protein, plant essential oils or extracts to extend the quality and shelf life of meat and meat products: A systematic review

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Abstract

Meat and meat products are highly susceptible to microbial spoilage and lipid oxidation, leading to rapid deterioration in quality and shortened shelf life. The growing concerns regarding synthetic preservatives have increased the interest in natural biodegradable alternatives. Whey protein isolate (WPI), a dairy by-product, offers excellent film-forming ability and oxygen barrier properties, making it a promising matrix for active edible coatings and films. This systematic review, conducted according to Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, included a comprehensive literature search that was performed on Scopus and PubMed databases for original English-language articles published between 2010 and 2025. Eight original studies met the strict inclusion criteria, reporting the application of WPI or whey protein concentrate (WPC) films/coatings containing plant essential oils (EOs) or extracts to meat or meat products during storage. Gas chromatography–mass spectrometry (GC-MS) analyses consistently identified phenolic monoterpenes (thymol, carvacrol, and eugenol) and diterpenes (carnosic acid and rosmarinic acid) as the primary bioactive compounds. Whey protein-EO systems reduced total viable counts by 1–5 $\log_{10}$ CFU/g and lipid oxidation markers (thiobarbituric acid reactive substances and peroxide value) by 30–60% compared to controls. Thyme and *Trachyspermum copticum* EOs exhibited the strongest antimicrobial activity, whereas rosemary and laurel provided superior antioxidant protection. Nanoencapsulated and Pickering emulsion formulations consistently outperformed free EOs through sustained release. Whey protein–plant bioactive composites effectively extend the shelf life of meat and meat products through dual antimicrobial and antioxidant mechanisms, representing sustainable and clean-label solutions that support product safety and circular economy principles by valorizing dairy and plant by-products.

Keywords: Botanical, Coating, Film, Meat, Meat Products, Whey Protein.

Introduction

Meat and meat products are vital components of the global diet, providing high-quality proteins, essential amino acids, vitamins, and minerals. However, their high water activity, neutral pH, and rich content of polyunsaturated fatty acids make them highly susceptible to quality deterioration during storage. Microbial proliferation, primarily by psychrotrophic bacteria such as *Pseudomonas* spp., *Brochothrix thermosphacta,* lactic acid bacteria (LAB), *Enterobacteriaceae*, and yeasts, along with chemical changes including lipid oxidation, leads to off-flavors, rancidity, discoloration, texture softening, and nutrient loss, significantly shortening shelf life and raising food safety concerns (Akcan et al., 2017; Tsironi et al., 2022). Lipid oxidation generates

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secondary products, such as malondialdehyde, while microbial metabolism produces biogenic amines and volatile compounds that compromise sensory acceptability and consumer safety. Conventional synthetic antioxidants and plastic packaging offer partial solutions but face limitations due to health perceptions, regulatory restrictions, and environmental impacts, driving the search for natural and biodegradable alternatives (Carvalho et al., 2019; Esmaeili et al., 2020; Mostafavi & Zaeim, 2020).

Edible films and coatings based on WPI, a valuable dairy by-product, have gained prominence as sustainable packaging materials for meat. Whey protein exhibits excellent film-forming ability through thermal denaturation and hydrogen bonding, yielding transparent, flexible films with strong oxygen and aroma barrier properties that effectively limit oxidative reactions and volatile loss in meat-containing products. These biopolymer matrices are biodegradable, edible, and generally recognized as safe (GRAS) (Akcan et al., 2017; Tsironi et al., 2022). When applied as coatings or films, WPI materials serve as physical barriers against moisture migration and oxygen ingress, thereby retarding enzymatic autolysis, lipid peroxidation, and surface microbial contamination in comminuted or whole meat cuts during refrigerated or frozen storage (Carvalho et al., 2019).

The functionality of whey protein films is markedly enhanced by incorporating essential oils (EOs) and extracts, which serve as natural antimicrobial and antioxidant agents. Several studies have also indicated the antimicrobial activities of WPC edible films incorporated with different EOs rich in phenolic compounds, such as thymol, carvacrol, rosmarinic acid, and eugenol, from sources such as thyme, rosemary, sage, laurel, ginger, and garlic. These bioactive compounds disrupt bacterial cell membranes, inhibit enzyme activity, and scavenge free radicals, providing active protection beyond passive barriers (Akcan et al., 2017; Catarino et al., 2017; Esmaeili et al., 2020). Nanoencapsulation or direct integration allows for controlled release, optimizing efficacy while minimizing sensory impacts. These composite systems combine the inherent oxygen-barrier capacity of whey protein with the bioactive potency of plant derivatives, effectively addressing both microbial spoilage and chemical oxidation in meat matrices (Carvalho et al., 2019; Tsironi et al., 2022).

Whey protein-based coatings and films reduce the need for synthetic preservatives, extend the shelf life under various storage conditions, and maintain desirable physicochemical attributes, including color stability, pH balance, and texture. By mitigating total viable counts (TVCs), specific spoilage organisms, and markers of lipid oxidation, these active packaging solutions enhance product safety and sensory quality throughout the supply chain (Akcan et al., 2017; Esmaeili et al., 2020). Furthermore, they support circular economy principles by repurposing whey and plant byproducts.

This article reviews the application of whey protein and EOs or extracts in edible films and coatings to improve the quality and shelf life of meat and meat products during storage. It highlights formulation strategies, mechanisms underlying antimicrobial and antioxidant effects, interactions with meat components, and performance across different meat systems, underscoring the potential of these biobased technologies for sustainable packaging.

Materials and Methods

Methodology

This systematic review was performed in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Moher et al., 2010) (**Fig. 1**). Systematic reviews conducted according to the PRISMA framework enable readers to reproduce the literature search and selection processes, thereby minimizing selection bias when identifying relevant studies.

Search strategy

A comprehensive literature search was conducted in international databases, including Scopus and PubMed, to explore original publications related to the use of whey protein coating or film containing EO or extract in the improvement of meat or meat products during storage, in the English language, on May 1, 2026. A time restriction of 2010–2025 was applied. In total, thirty-eight articles were obtained. We used combinations of the MeSH terms/keywords "essential oil" or "extract" and "whey protein" and "coating" or "film," and "Meat or "meat product" or "salami" or "sausage."

Selection of articles

After duplicate records were removed, two independent reviewers screened the titles and abstracts of the identified studies for their eligibility. The full texts of potentially relevant articles were subsequently assessed in detail. Any discrepancies were resolved through discussion or consultation with a third reviewer, when necessary.

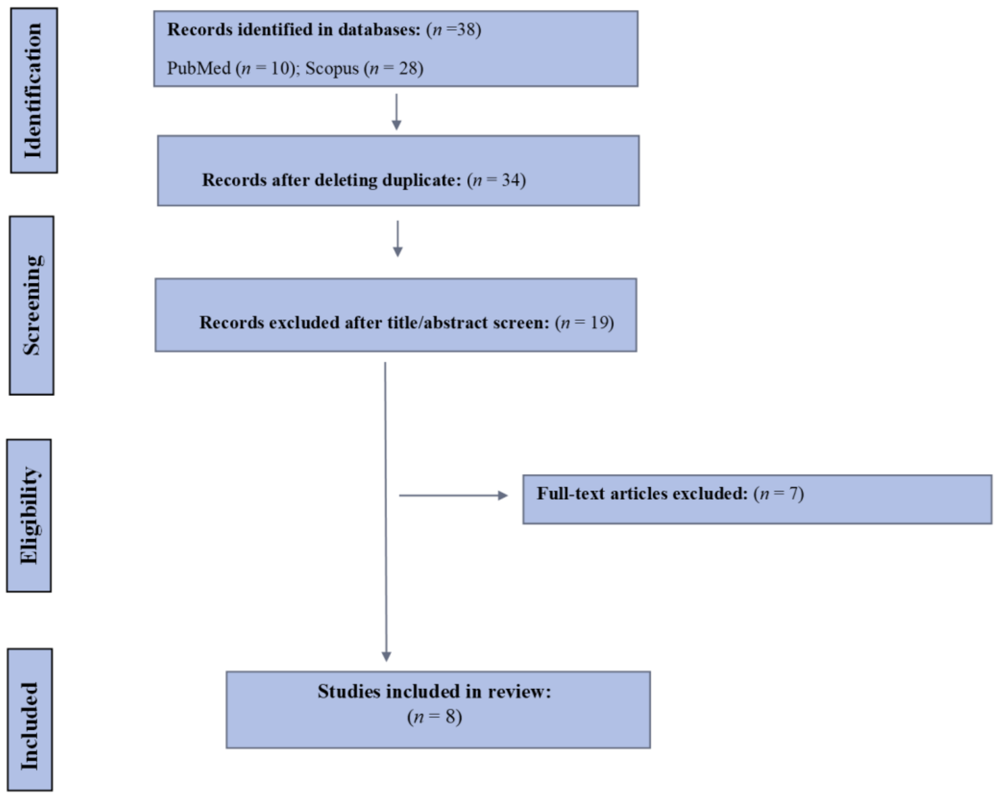

Figure 1. PRISM flowchart showing study selection process.

Inclusion and exclusion criteria

A systematic literature review was performed on English-language publications. Although the initial search identified a substantial number of studies, only original research articles were included. Eligible studies were required to report the development or application of whey protein-based coatings or films incorporating EOs or extracts in meat and meat products during their storage. This study included only articles in which whey protein was used alone as a coating or film for the preservation of meat and meat products. Therefore, studies focusing on incorporating other biopolymers or materials (e.g., cellulose, alginate, chitosan, or starch) in combination with whey protein as part of composite coatings or films, as well as studies that did not include EOs or extracts were excluded from this review. Studies conducted on non-meat food matrices (e.g., fish, seafood, dairy products, fruits, vegetables, or plant-based protein analogues) were excluded, limiting the scope strictly to meat and meat products. In addition, full-text availability and sufficient quantitative data on the reduction of pathogenic and/or spoilage microorganisms and relevant chemical quality parameters were mandatory inclusion criteria.

Data extraction

Two independent reviewers extracted data from the included studies. The following information was collected: first author's name, publication year, whey protein coating or film, method of preparation of coating or film, plant species, composition of EO, method of preparation of extract and EO, type of meat or meat products and treatments, storage temperature, storage duration and intervals of assays, and results of antimicrobial or chemical analyses. Discrepancies between reviewers were resolved by discussion. When consensus could not be reached, a third reviewer was consulted.

Table 1. Whey protein coating or film, EOs or extracts, and treatments during storage of different meat and meat products

Coating or film and concentration	Plant species, EOs or extract	Type of meat and meat product and treatments	Reference
Film (5%)	*Laurus nobilis* and *Salvia officinalis* extracts	Cooked meatballs (boneless beef) Control WPF/ 2% LA+WPFs/ 4% LA+WPFs/ 2% SA+WPF / 4% SA+WPF	Akcan et al., 2017
Film (8%)	Rosemary extract	Salami control film (without the rosemary extract) or with the active whey protein film (with 1% (w/w) of the rosemary extract)/ were packaged in vacuum conditions	Andrade et al., 2019
Film (5%)	Cinnamon, cumin, thyme EO	Fresh beef Unwrapped (control)/ wrapped with EOs-films 1%, 1.5%, 2%, 2.5%	Badr et al., 2014
Coating (10%)	*Origanum virens* EO	Traditional Portuguese sausages (Paínhos and Alheiras) coated painhos 1%/ coated Alheiras 1%/ uncoated Painhos/ uncoated Alheiras)	Catarino et al., 2017
Coating (5%)	Thyme, rosemary, basil, pimento and coriander EOs	Sliced bologna-type sausage Control/ coated with 4% of each EOs and nisin	Kalkan et al., 2020
Coating (8%)	*Trachyspermum copticum* EO	Beef Control / coated with whey / coated with whey and EOs (whey-EOs) 0.1%/ coated with whey and Pickering emulsion of EOs (whey-NEO) 5%	Saghari et al., 2024
Film (8%)	*Cinnamomum cassia*, *Cinnamomum zeylanicum*, and *Rosmarinus officinalis* EOs	Salami WP0 (control, without EOs), WP1 (with 1% of EOs blend), WP2 (with 2% of EOs blend), WP 2.7 (with 2.7% of EO blend), and WP5 (with 5% of EO blend)	Ribeiro-Santos et al., 2017
Film (8%)	Ginger and rosemary	Minced Lamb Meat WP film / WP + ginger 0.5% / WP + ginger 1% / WP + rosemary 0.5% / WP + rosemary 1%	Tsironi et al., 2022

Results and Discussion

The systematic literature search initially yielded thirty-eight articles from the selected databases. After removing duplicates and screening titles and abstracts for relevance, 15 articles were selected for full-text evaluation. Seven were excluded due to insufficient data or failure to meet the predefined inclusion and exclusion criteria. Ultimately, eight studies fulfilled all eligibility requirements and were included in the systematic review, and related information was collected (**Table 1** and **Table 2**).

In recent years, the formulation of edible coatings and films using biopolymers combined with natural bioactive compounds has attracted considerable interest as a means of enhancing the preservation of perishable foods. Among these biopolymers, whey protein, a by-product of cheese manufacturing, offers excellent film-forming properties, gas barrier capacity, and biodegradability. When integrated with EOs or extracts, whey protein-based edible coatings or films have emerged as an effective, natural intervention strategy to extend the shelf life of meat products. The preservative effect of these biocomposite systems on meat and meat products is primarily attributed to their multifunctional mechanisms: (i) mitigation of microbial spoilage resulting from the antimicrobial activity of phenolic and terpenoid compounds present in EOs and extracts (Badr et al., 2014; Catarino et al., 2017; Kalkan & Erginkaya, 2019; Saghari et al., 2024; Tsironi et al., 2022); (ii) retardation of lipid oxidation due to the radical scavenging and metal-chelating properties of the incorporated phytochemicals (Akcan et al., 2017; Andrade et al., 2019; Catarino et al., 2017; Saghari et al., 2024; Tsironi et al., 2022). This systematic review synthesizes findings from multiple studies highlighting the synergistic benefits of these bio-based systems.

Table 2. Effect of whey protein coating or film contained EOs or extracts on chemical and microbial properties of meat and meat products during storage

Pathogen and reduction rate	Lipid oxidation and chemical change	Reference
-	TBA lower in whey protein contained natural antioxidant treatments; Higher antioxidant activity by LA-WPF than SA-WPF; TBA LA4-WPF showed best results	Akcan et al., 2017
-	Active film was able to delay the salami's lipid oxidation for, at least, 30 days	Andrade et al., 2019
Total viable count reduction, greater antimicrobial activity in thyme contained treatment	-	Badr et al., 2014
Inhibition of the total microbial load for both coated sausages	Coated Alheiras had a significant reduction of the lipid peroxidation	Catarino et al., 2017
Inhibition of *L. innocua*; The most effective coatings were coating contained pimento EOs	-	Kalkan et al., 2020
The highest and lowest microbiological counts were related to control samples and whey- Pickering emulsion EO (NEO) treatments. total viable count, total psychrotrophic count, and the lactic acid bacteria count was more reduced in whey-NEO treatments	After 18 days, the lower results for PV, TBARs, and TVB-N values were showed in whey- NEO treatment	Saghari et al., 2024
-	Films incorporating EOs significantly reduced the oxidation status. All active films were effective against lipid oxidation in comparison with control film, and no significative differences among them at 90 and 180 days was noticed	Ribeiro-Santos et al., 2017
Films with 1% EOs significantly improved the microbiological quality of meat. Total viable counts, Pseudomonas spp., *Br. thermosphacta*, lactic acid bacteria, *Enterobacteriaceae*, and yeasts remained low for films with 1% concentration of essential oil compared with 0.5%	Oxidation degree was significantly reduced	Tsironi et al., 2022

Main components of EOs and antimicrobial mechanisms

A consistent finding across the included studies was the direct relationship between the chemical profile of EOs or extracts and their preservative efficacy in meat systems. GC-MS analyses revealed that the biological activity is primarily attributable to specific phenolic monoterpenes and aldehydes, although the dominant compounds varied markedly by plant source.

Among the most frequently characterized botanicals, laurel (*Laurus nobilis*) extract is consistently rich in eugenol and related phenolic derivatives. In contrast, sage (*Salvia officinalis*) exhibited high concentrations of carnosol, carnosic acid, and rosmarinic acid diterpenes known for both antioxidant and antimicrobial properties (Akcan et al., 2017). Cinnamon EO is dominated by cinnamaldehyde, cumin EOs features cuminaldehyde and γ-terpinene, and thyme EOs contains thymol and carvacrol as its major constituents (Badr et al., 2014). The main components identified were gingerol and shogaol, along with rosemary derivatives, including 1,8-cineole, camphor, and α-pinene (Tsironi et al., 2022). A high thymol content (42.03%) was also reported for *Trachyspermum copticum* EO, accompanied by p-cymene (22.27%), γ-terpinene (15.36%), carvacrol (4.73%), β-Pinene (3.97%), and octyl butyrate (3.1%) (Saghari et al., 2024). Importantly, the compositional profiles were not uniform, even within the same genus. For example, *Origanum virens* (*O. virens*) EO incorporated into WPC coatings for Portuguese sausages (Paínhos and Alheiras) contained carvacrol (21.8%), γ-terpinene (20.8%), thymol (12.1%), p-cymene (6.1%), and β-caryophyllene (6.0%), terpinen-4-ol (5.3%), beta-bisabolene (4.5%), and 4-carene (3.8%). This chemotype differs from other oregano species, where thymol may predominate, underscoring the necessity of chemical standardization in systematic reviews (Catarino et al., 2017). Similarly, Seydim and Sarikus (2006) reported that oregano and rosemary EOs embedded in WPI films retained strong antimicrobial activity, which they attributed to the high phenolic content of the EOs rather than the whey protein matrix itself. However, the whey protein matrix likely serves as a controlled-release vehicle, stabilizing volatile EOs components and prolonging their contact time with meat surfaces. These phenolic monoterpenes (e.g., thymol, carvacrol, and eugenol) exert antimicrobial activity primarily by disrupting bacterial cell membranes. Their lipophilic nature allows them to partition into lipid bilayers, increasing permeability, causing leakage of intracellular contents (e.g., ATP and ions), and leading to cell death. Additional mechanisms include inhibition of efflux pumps, interference with quorum sensing, enzyme inactivation, and generation of reactive oxygen species (ROS) (Burt, 2004). Gram-positive bacteria are generally more susceptible to EOs due to the absence of an outer lipopolysaccharide layer. However, synergistic effects with minor components (e.g., p-cymene enhancing carvacrol penetration) broaden the efficacy against Gram-negative bacteria such as *Pseudomonas* and *Enterobacteriaceae* (Khwaza & Aderibigbe, 2025).

Effect of extract type, concentration, plant species, and other factors on antimicrobial activity

Antimicrobial efficacy varied significantly depending on the plant source, extraction method, concentration, and application form. Higher EOs concentrations (e.g., 1% vs. 0.5%) generally produced stronger reductions in TVCs, psychrotrophs, and LAB, often extending the shelf life by 6–12 days under refrigeration (Saghari et al., 2024; Tsironi et al., 2022). Phenol-rich oils (thyme, oregano-like *Trachyspermum*, and sage) outperformed the other oils because of their higher thymol/carvacrol content. Seasonal and geographic variations influenced composition; for instance, higher phenolic levels in certain harvests enhanced activity. Nano-or Pickering emulsions outperform free EOs by improving stability, controlling release and penetration, reducing required doses, and minimizing sensory impacts (Saghari et al., 2024). Factors such as pH, temperature, and meat matrix composition (fat content and proteins) modulated activity, with synergistic interactions between whey's oxygen-barrier properties and bioactives amplifying effects of EOs.

Antimicrobial effect of using EOs or extract in whey protein-based film or coating during meat and meat product storage

The integration of WPI-based edible films and coatings with EOs or extracts consistently demonstrated significant antimicrobial efficacy across the reviewed studies, aligning with the research objective of extending the shelf life of meat or meat products during refrigerated or frozen storage.

The results of a comparative study by Badr et al. (2014) demonstrated that thyme EO-WPI films were most effective against fresh beef spoilage flora, reducing the TVC by more than 4 $\log_{10}$ CFU/g at

2.5% concentration after 12 d of storage at 5 °C, with sampling at 2-day intervals. This level of reduction was notably greater than that achieved with cinnamon or cumin EOs at equivalent concentrations. This aligns with the findings of Oussalah et al. (2004), who reported similar thyme/cinnamon efficacy in milk protein films on beef, attributing the superior thyme performance to the higher thymol content.

Tsironi et al. (2022) showed that 1% rosemary or ginger EOs in WPI films best controlled TVC and *Pseudomonas* in minced lamb. These outcomes parallel Zinoviadou et al. (2010), who noted whey films with oregano EOs effectively inhibited spoilage flora on beef. A notable advancement identified in recent studies is the improved antimicrobial activity achieved when EOs are delivered via nano-encapsulation or Pickering emulsion systems rather than in a free form. Saghari et al. (2024) highlighted the superiority of Pickering emulsion *T. copticum* EO-WPI coatings, which yielded significantly lower values for TVC, LAB, peroxide value (PV), thiobarbituric acid reactive substance (TBARS), and total volatile basic nitrogen (TVB-N) in refrigerated beef compared to free EOs forms. This advantage of nano-delivery systems is consistent with the findings of Ghaderi-Ghahfarokhi et al. (2017) and Zomorodian et al. (2023), where encapsulated EOs provided sustained release and enhanced efficacy at reduced concentrations.

Catarino et al. (2017) applied a WPC coating containing *O. virens* EO (1% w/w) to two traditional Portuguese sausages (Paínhos and Alheiras). The coating reduced the total viable aerobic count, extending shelf life by approximately 20 days for Paínhos in storage for 4 months (sampling at 21, 49, 75, 100, 126 days) and 15 days for Alheiras in storage for 106 days (sampling at 14, 36, 58, 80, 106 days), compared to uncoated controls. Notably, the EO-WPC coating favored the growth of LAB, which is beneficial for fermentation and preservation.

Kalkan and Erginkaya (2020) evaluated WPI coatings containing various EOs at 4 % (w/v) and other antimicrobials, such as nisin, potassium sorbate, and sodium benzoate, in bologna-type sausage which stored in refrigerator for 35 days, with sampling performed at 1, 7, 14, 21, 28, and 35 days. The most effective inactivation of *Listeria innocua* was achieved using potassium sorbate, sodium benzoate, and pimento EOs. Nisin-WPI coatings also reduced bacterial counts. Zinoviadou et al. (2009) reported that WPI films with 1.5% oregano oil significantly reduced the TVCs of fresh beef. The antimicrobial mechanism is primarily attributed to phenolic compounds (e.g., carvacrol and thymol) that disrupt bacterial cell membranes, leading to the leakage of intracellular contents and cell death (Burt, 2004).

Control of lipid oxidation in meat and meat products during storage by using EOs or extract in whey protein-based film or coating

Lipid oxidation is a primary cause of quality deterioration in meat products, leading to off-flavors, discoloration, and loss of nutritional value. Several studies have demonstrated that whey protein-based films and coatings incorporating EOs or extracts can effectively retard lipid oxidation in meat products during refrigeration. Across the reviewed studies, the incorporation of EOs or extracts into WPI or WPC films and coatings consistently retarded oxidative changes. The protective effect is attributed to a dual mechanism: (i) the physical barrier properties of the whey protein matrix against oxygen ingress and (ii) the controlled release of bioactive phenolic compounds that scavenge free radicals and chelate pro-oxidant metal ions.

The efficacy of whey protein-based active packaging is frequently quantified using TBARS, PV, p-anisidine value (p-Av), and conjugated dienes (CD) as biomarkers of lipid peroxidation. In a comparative study by Akcan et al. (2017), whey films containing laurel extracts (rich in eugenol and phenolics) were more effective than sage in lowering TBARS, PV, p-Av, and CD in frozen cooked meatballs over 60 days at −18°C, with sampling every 15 days. Laurel treatments maintained significantly lower TBARS and p-Av values compared to controls, attributed to high total phenolic content and radical-scavenging capacity (measured by 2,2-diphenyl-1-picrylhydrazyl (DPPH)). These findings are consistent with those of Estévez et al. (2007), who reported that sage and rosemary EOs in liver pâté reduced TBARS more effectively than the synthetic antioxidant butylated hydroxytoluene during refrigerated storage.

Tsironi et al. (2022) demonstrated that 1% rosemary or ginger EOs in WPI films markedly suppressed TBARS development in minced lamb for 11 days at 4 °C (days 0, 2, 5, 8, and 11), with rosemary providing superior inhibition. These findings are consistent with those of Socaciu et al. (2021), who reported reduced TBARS in fish coated with whey-tarragon films.

A consistent finding in recent studies is the superior antioxidant performance of EOs delivered in encapsulated or Pickering emulsion forms compared to free (unencapsulated) EOs. Saghari et al. (2024) further showed that Pickering emulsion forms of *T. copticum* EOs in whey coatings achieved the lowest PV (9.8 meq/kg) and TBARS (5.45 mg MDA/kg) in refrigerated beef after 18 d, with analyses conducted at 3-day intervals (days 0, 3, 6, 9, 12, 15, and 18). outperforming free EO and control samples (13.9 meq/kg and 8.85 mg MDA/kg, respectively). The superior performance of nanoencapsulated forms is consistent with the findings of Ghaderi-Ghahfarokhi et al. (2017) and Zomorodian et al. (2023), who noted enhanced oxidative stability with encapsulated EOs due to improved stability and sustained release.

The magnitude of antioxidant protection was influenced by both the fat content of the meat product and the concentration of bioactive agents in the whey-protein matrix. Andrade et al. (2019) evaluated a whey protein film containing 1% rosemary extract on salami slices stored at 5°C for 90 days, with assessments carried out on days 0, 7, 15, 30, 60, and 90. The active film significantly reduced hexanal content and TBARS compared to the control film, delaying lipid oxidation for at least 30 d. All TBARS values remained below 0.5 mg MDA/kg, the threshold for off-flavor perception by consumers. Similarly, Catarino et al. (2017) applied a WPC coating with 1% *O. virens* EOs to Portuguese sausages (Paínhos and Alheiras). In Alheiras (higher fat content, approximately 23 g/100 g), the coating reduced malondialdehyde formation, with a maximum difference observed at 106 days (1.96 vs. 2.88 mg MDA/kg for coated and uncoated samples, respectively). Ribeiro-Santos et al. (2017) incorporated a blend of cinnamon and rosemary EOs (1–5% w/w) into whey protein films and packaged salami for up to 180 days in refrigerated storage (intervals of 0, 4, 7, 15, 30, 45, 60, 90, 135, and 180). The film with a 5% EOs blend was the most effective, significantly reducing hexanal and TBARS values compared to the control after 180 days.

The antioxidant mechanism is attributed to phenolic compounds (e.g., carnosic acid, rosmarinic acid, carvacrol, thymol, and cinnamaldehyde) that scavenge free radicals, chelate pro-oxidant metals, and break the chain reaction of lipid peroxidation (Burt, 2004; Ribeiro-Santos et al., 2018). These findings confirm that whey protein-based active packaging with natural EOs or extracts effectively controls lipid oxidation, thereby extending the shelf life of meat products. These outcomes align with the broader literature demonstrating the efficacy of whey-EO coatings in retarding oxidative changes in meat (Fernández-Pan et al., 2014).

This review exclusively included studies conducted on meat matrices, specifically beef, lamb, sausage, and meatball matrices. Furthermore, only English-language articles indexed in Scopus and PubMed were included, which may have introduced potential language and publication biases. Future systematic reviews should consider including non-English sources to reduce this bias.

Conclusion

The compiled findings demonstrate that WPI and WPC matrices serve as effective carriers for bioactive phenolic compounds, including thymol, carvacrol, eugenol, and rosmarinic acid, derived from thyme, rosemary, sage, laurel, ginger, cinnamon, and *T. copticum*. These composite systems exert dual preservative actions: (i) antimicrobial effects through disruption of bacterial cell membranes, leading to leakage of intracellular contents and reduced viable counts of spoilage organisms, and (ii) antioxidant effects via free radical scavenging and metal chelation, significantly retarding lipid oxidation, as measured by TBARS, PV, and hexanal formation. Notably, nanoencapsulated and Pickering emulsion formulations consistently outperformed free EOs by enabling sustained release and enhancing stability. Collectively, whey protein–

plant bioactive composites represent a sustainable, clean-label alternative to synthetic preservatives and plastic packaging, supporting circular economy principles by valorizing dairy by-products.

Conflicts of interest

The authors declare no conflict of interest.

Disclaimer

The authors acknowledge the use of artificial intelligence tools (including Grammarly's paraphrasing feature, Deepseek, and Grok) to enhance the linguistic clarity, coherence, and scholarly quality of the manuscript. The core intellectual content, analysis, and final authorship remain the sole responsibilities of human contributors.

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