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Plant-based preservation of meat: a critical narrative review of bioactive extracts, essential oils, and next-generation delivery systems

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The increasing demand for natural and sustainable food preservatives has driven growing interest in plant-derived bioactives as alternatives to synthetic additives such as nitrites and sulfites. Essential oils (EOs) and plant extracts, especially from rosemary (*Rosmarinus officinalis*), oregano (*Origanum vulgare*), Thyme (*Thymus vulgaris*) and clove (*Syzygium aromaticum*), exhibit strong antimicrobial and antioxidant activities that inhibit lipid oxidation, control spoilage and pathogenic bacteria, and extend meat shelf life during refrigerated storage. This review critically examines the mechanisms of key phytochemicals (phenolics, terpenoids, and flavonoids) and recent technological advances enhancing their performance. Emerging strategies such as nanoemulsions, electrospun nanofibers, biopolymer coatings, and smart packaging enable controlled release and improved stability of bioactives while reducing sensory impact. Green extraction methods, including supercritical CO₂ and ultrasound-assisted techniques, further contribute to the recovery of heat-sensitive compounds with reduced environmental footprint. Despite these advances, several barriers, such as compositional variability, production cost, and regulatory uncertainty, continue to limit large-scale implementation. Addressing these challenges will require integrated research combining toxicological validation, life-cycle assessment, and synergistic formulation with non-thermal preservation methods. By linking breakthroughs in nanotechnology and green chemistry with industrial scalability, this review reframes plant-based meat preservation as a multifunctional, intelligent, and sustainable system, offering a roadmap for developing safe, efficient, and eco-friendly alternatives to conventional preservatives in the global meat industry.

KEYWORDS

active packaging, antimicrobial activity, essential oils, meat preservation, oxidative stability, plants, smart packaging

1 Introduction

Meat is an important source of high-quality proteins, essential fatty acids, vitamins, and minerals. However, its high moisture content, nutrient-rich composition, and near-neutral pH create an ideal environment for microbial growth and lipid oxidation, which significantly limit shelf life and compromise safety and quality (Uhlir et al., 2024). The current regular

preservation relies heavily on synthetic additives, refrigeration, and modified atmosphere packaging, yet growing consumer preference for natural, minimally processed foods has driven the search for alternative preservation strategies (Gómez et al., 2020). It was observed that, the increasing consumer demand for natural and sustainable alternatives to synthetic preservatives (such as nitrites and nitrates, benzoates, sorbates, and sulfites) has driven significant interest in harnessing plant-derived compounds for food preservation (Suliman et al., 2023). The widespread use of food additives in meat products has emerged as a significant public health concern in many countries. Consequently the food industry should prioritize the development and adoption of natural alternatives for the safe processing and storage of meat (Amin et al., 2018). The utilization of plants in health and food applications has gained significant momentum in recent years, driven by a growing body of high-impact research highlighting the antioxidant potential of their natural bioactive compounds. This expansion of scientific evidence underscores the promising future of plant-based approaches in both pharmaceutical and food processing sectors (Al-Mijalli et al., 2025; Giwa et al., 2025). Among these, essential oils and plant extracts stand out as promising candidates, offering potent antimicrobial and antioxidant properties to extend the shelf life of perishable products like meat (Angane et al., 2022; Awad et al., 2022). Meat and poultry support the growth of several key foodborne pathogens. *Salmonella* spp. are among the leading causes of meat-associated gastroenteritis globally, frequently linked to contaminated poultry and undercooked products (Scallan et al., 2011). *Listeria monocytogenes* is particularly important in chilled, ready-to-eat meat, because it can grow at refrigeration temperatures and cause severe invasive listeriosis in vulnerable groups. Shiga toxin-producing *Escherichia coli* (e.g., O157:H7) is associated mainly with beef and sometimes poultry, where inadequate cooking or cross-contamination can lead to hemorrhagic colitis and hemolytic uremic syndrome. In addition, modern technologies such as vacuum or modified-atmosphere packaging of red meat create anaerobic conditions that can permit the germination and toxin production of non-proteolytic *Clostridium botulinum* if temperature and other hurdles are not adequately controlled (Peck, 2006). This justifies treating *C. botulinum* as a critical hazard in chilled, vacuum-packed meats, despite botulism being relatively rare compared with salmonellosis or listeriosis.

For thousands of years, red meat has served as a key source of nutrition, it comes from animals such as cattle (beef), sheep (lamb, mutton), goats (chevon), deer (venison), and pigs (pork), recognized for their darker muscle tissue. The red hue of raw meat primarily results from the presence of myoglobin in adequately bled animals (Ruxton and Gordon, 2024). Poultry meat, which refers to the meat obtained from domesticated birds such as chickens, turkeys, ducks, and geese, is regarded as the most significant contributor among food supplies. Poultry meat accounted for approximately 40% of global meat production in 2020, a trend that has been consistently observed over the past three decades (Bist et al., 2024). Furthermore, fish meat and aquatic food products have been fundamental components of human diets, especially for people residing in coastal regions. Fish and fish-derived products are recognized among the most nutritious and health-enhancing dietary sources worldwide (Tacon and Metian, 2013). Global meat production has shown a dramatic increase since the early 1960s,

reflecting rising demand, improvements in livestock production technologies, and changing consumption patterns. According to data compiled from the Food and Agriculture Organization of the United Nations (FAO) covering the period from 1961 to 2023, total global meat output has grown more than four-fold, indicating substantial structural shifts in the industry (Figure 1).

In general, all meat types and their products are perishable food materials that need to be preserved with additives to prevent harmful foodborne microorganisms and pathogens from causing spoilage (Yu et al., 2021; Mahmud et al., 2023; Marcelli et al., 2024). Several plant based materials could be used to enhance quality of meat and meat products with the objectives of but not limited to improving composition, fatty acid profile, reducing levels of fat and cholesterol, and enhancing the health of the consumer (Espinales et al., 2024). According to Butnariu and Sarac (2019), the three fundamental criteria for qualifying as a functional food ingredient are: (1) the ingredient must be naturally occurring or derived, (2) it must be consumed as part of the regular diet, and (3) It should primarily support product quality and safety when used as a natural substitute for synthetic additives. Growing consumer preference for products without artificial preservatives has driven researchers to explore innovative sources of antibacterial compounds (Pinto et al., 2023). These objectives are satisfied by the application of extracts and essential oils of some medicinal plants, which have been shown to be effective in improving the quality and safety of meat and meat products. Among these plants, clove, cinnamon, coriander, rosemary, oregano, thyme and sage have demonstrated a higher inhibition effect in the growth of microbes and lipid oxidation and they are classified as generally recognized as safe (Bor et al., 2016; Ortega-Lozano et al., 2023). The growing concern over the negative effects of synthetic preservatives has led to increased interest in natural alternatives (Alirezalu et al., 2020). In this context, plants have emerged as a valuable source of bioactive compounds with antimicrobial and antioxidant properties. These include alkaloids, phenolic compounds, carotenoids, terpenoids, and sulfur-containing phytochemicals, among others (Nieto, 2020; Sadeek and Abdallah, 2019). Such compounds are typically found in various parts of the plant like bark, leaves, roots, fruits, flowers, and stems and are often extracted in the form of essential oils or plant extracts. These extracts are complex mixtures of low molecular weight volatile substances derived from several plant families, including Rutaceae, Lauraceae, Myrtaceae, Zingiberaceae, and Umbelliferae (Jaworska and Sadowska, 2024; Kumar et al., 2023). Recent studies have increasingly investigated the use of these natural compounds to enhance the quality and safety of meat and meat products (Jose et al., 2018; Munekata et al., 2024). While numerous studies have explored these approaches, much of the literature is fragmented, focusing on specific extracts, single meat types, or isolated packaging methods (Holley and Patel, 2005). The present work therefore adopts a critical narrative review approach to integrate advances from 2012 to 2024 and to highlight practical challenges—such as sensory thresholds, toxicology, regulatory limits, and scale-up gaps, as well as opportunities for industrial translation. This article aims to review the latest advancements in the application of selected plant extracts and their essential oils in the meat industry, in line with the growing demand for clean-label and natural food solutions.

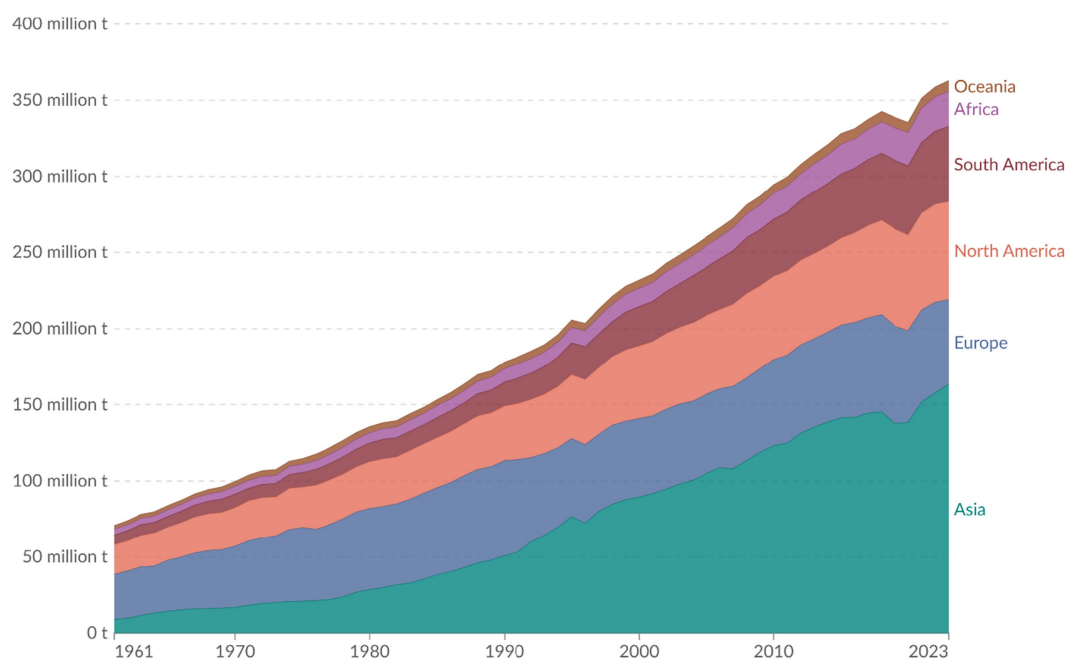


FIGURE 1

Global meat production, 1961 to 2023. Data source: Food and Agriculture Organization of the United Nations (2025): <https://ourworldindata.org/meat-production> (No permission required: CC BY). The line graph shows the total worldwide production of meat in million tonnes over time. The data is further broken down by continental regions, including Asia, Europe, North America, South America, Africa, and Oceania. The overall trend shows a dramatic increase, more than quadrupling over the six-decade period.

2 Methodology

A comprehensive literature search was conducted to gather relevant information from published studies available in well-established online databases, including PubMed, Web of Science, Scopus, and ScienceDirect. Only publications in English were considered, ensuring accessibility and consistency in data interpretation. The search focused on peer-reviewed articles, book chapters, and conference proceedings published between 2012 and 2024, using specific keywords such as “plant extracts” AND “meat preservation,” “essential oils” AND “antimicrobial activity” AND “meat,” “natural antioxidants” AND “lipid oxidation” AND “meat products”; “edible coatings,” “nanoencapsulation,” “electrospinning,” “smart packaging” and “meat preservation.”

2.1 Inclusion/exclusion criteria

Studies included in this review were selected based on specific eligibility criteria to ensure relevance and scientific rigor. Only peer-reviewed articles, book chapters, and conference proceedings focusing on the application of plant extracts and essential oils in meat and meat products, such as beef, poultry, and fish, were considered. Studies investigating antimicrobial, antioxidant, or preservative effects, including lipid oxidation inhibition and microbial load reduction, were prioritized. Research incorporating advanced and up-to-date technologies such as nanoencapsulation, electrospinning, and smart packaging for plant extract delivery was also included. Furthermore, studies were required to provide quantitative data, such as microbial reduction (e.g., log CFU/g decrease), oxidative stability indicators

(e.g., TBARS values), or shelf-life extension metrics. Explicit reporting of extract concentration, application method, and meat type was essential for inclusion. Only publications in English were reviewed to maintain consistency in interpretation. Studies were excluded if they focused on non-meat products (e.g., dairy, fruits) or synthetic additives, such as BHA and nitrites, or if they combined plant extracts with synthetic preservatives without isolating the natural effects. Research lacking experimental validation, such as opinion articles without original data, as well as duplicate studies, overlapping datasets, non-English publications, theses, or unpublished data, were omitted. Additionally, studies with incomplete methodologies, such as missing control groups, were excluded to maintain scientific integrity.

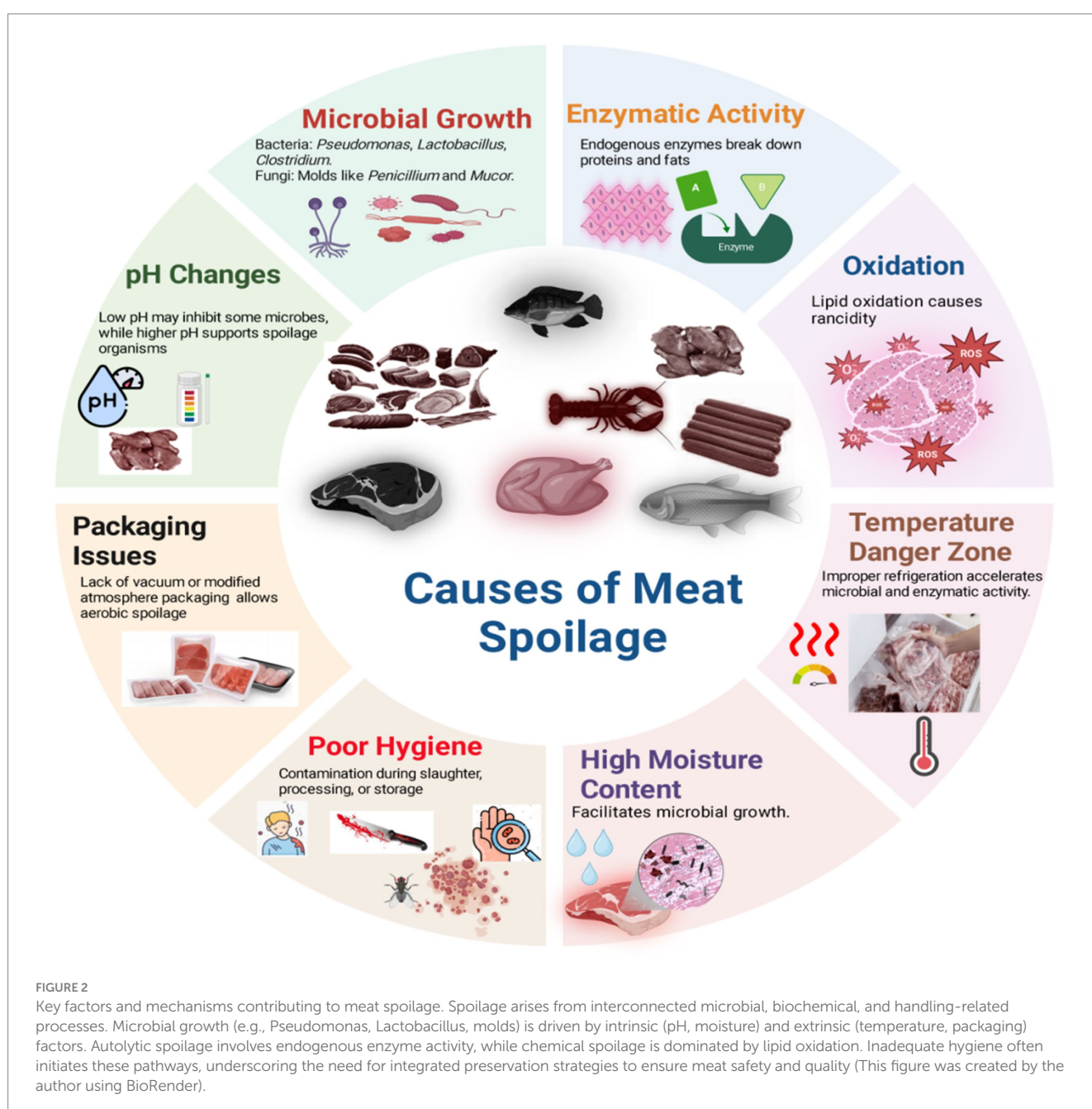
3 Meat spoilage: causes and preservation

The spread of foodborne illnesses caused by animal origin food products are a significant concern all over the world (Warmate and Onarinde, 2023). In recent years, the demand for meat products has risen progressively due to population growth and changing eating habits (Szenderák et al., 2022). As a result, the meat industry has become an important part of many economies and with increased demand comes the need for proper hygienic practices to ensure consumer safety (Parlasca and Qaim, 2022; Siluma et al., 2023). This is where novel preservation technologies such as edible films and coatings become relevant, as they extend shelf life, reduce economic losses from spoilage, and minimize product withdrawals related to safety concerns (Nunes et al., 2023). Overall, proper hygiene practices and new preservation technologies are crucial for a successful and

sustainable meat industry (Lisboa et al., 2024). The primary mechanisms and contributing factors leading to meat spoilage are summarized in Figure 2.

Meat and meat products are decomposed during processing and storage by three mechanisms: microbial spoilage, lipid oxidation and enzymatic autolysis (Luong et al., 2020; Dragoev, 2024; Uhlig et al., 2024). The microbial population can enter the meat through environmental, human, handling and storage conditions associated with the production chain or through the native microflora of the animal's skin and digestive tract (Marmion et al., 2021; Ali and Alsayeqh, 2022). The degradation of structural components, the reduction of the water binding capacity of the meat, odors and changes in the texture and appearance of the meat can all be caused by microbial growth (Anas et al., 2019; Pellissery et al., 2020). The

fatty acid composition, vitamin E content and pro-oxidants such as free iron in the muscles influence lipid oxidation (Wu et al., 2022). The degradation of lipids, pigments, proteins, carbohydrates, and vitamins generates oxidation products such as hydroperoxides, aldehydes, and ketones, which lead to off-flavors, color deterioration, and loss of nutritional value, ultimately compromising meat quality (Domínguez et al., 2019; Abeyrathne et al., 2021). Meat undergoes spoilage, resulting in a greenish color, due to enzymatic autolysis of proteins, fats, and carbohydrates and this process can lead to the growth of microorganisms (Addis, 2015; Mafe et al., 2024). Even when meat is stored at low temperatures (5 °C), proteolytic enzymes remain active, promoting microbial growth which contribute to a decrease in the water retention ability of meat and in the formation of biogenic amines (Schirone et al., 2022). Inadequate cooking and



cross-contamination during the handling, cutting, packaging, shipping, or processing of meat are frequent causes of outbreaks related to meat products (Das et al., 2019; Thakur et al., 2020). Certain toxins and spores can survive in cooked meat, causing foodborne diseases. Pathogenic microorganisms commonly associated with foodborne outbreaks include *Salmonella* spp., *Listeria* spp., *Clostridium* spp., *Staphylococcus* spp., and *Campylobacter* spp., leading to foodborne infections, intoxications, and toxico-infections (Lianou et al., 2017; Soni et al., 2016).

4 Antimicrobial and antioxidant activities of plant extracts and their essential oils

Plant extracts and their essential oils are increasingly studied for their antimicrobial and antioxidant properties, particularly in preserving meat and meat products (Ji et al., 2023; Olvera-Aguirre et al., 2023; Zhang and Piao, 2023). These alternative substances can extend meat's shelf life, prevent it from spoiling, and increase its safety without using synthetic ingredients (Bodie et al., 2024). They have been shown to inhibit the growth of various spoilage microorganisms and pathogens in meat and meat products such as *Salmonella*, *Escherichia coli*, *Listeria monocytogenes*, and *Staphylococcus aureus* (Efenberger-Szmechtyk et al., 2021). The antimicrobial effect of these extracts stems from several mechanisms such as cell membrane disruption, inhibition of enzymatic systems and biofilm inhibition. The main species responsible for spoilage of fresh and chilled meat include psychrotrophic microorganisms capable of growing at temperatures below 7°C, such as *Clostridium* spp., lactic acid bacteria, Enterobacteriaceae, and *Pseudomonas* spp. (Campolina et al., 2023). The effectiveness of plant extracts and their essential oils against microbes is directly correlated with their contents (Pellissery et al., 2020; Hosseini et al., 2021). Both plant extracts and essential oils work primarily by interacting with bacteria's cell membranes (Alizadeh-Sani et al., 2021). These natural chemicals can function by increasing membrane permeability, limiting the absorption of substrates required for microbial development, and interfering with cellular metabolism (Maurya et al., 2021). Moreover, phenolic compounds from plants and their essential oils can delay or prevent oxidation of meat fat and can chelate metals (e.g., iron, copper) that catalyze oxidation reactions, further preventing spoilage (Kalogianni et al., 2020).

Lipids oxidize to produce hydroperoxides, which in turn produce chemicals including undesirable volatile compounds such as aldehydes, ketones, acids, and alcohols (Geng et al., 2023). Proteins and amino acids undergo structural changes due to oxidation, which can reduce their digestibility, solubility, and bioavailability after consumption (Domínguez et al., 2021). When pigments oxidize, they produce brown chemicals, which affect the appearance of the meat. One of the primary pigments that gives the product its reddish color is myoglobin (Domínguez et al., 2018; Lorenzo et al., 2018). Plant extracts' antioxidant activity is mostly due to the presence of phenolic compounds. However, phenolic terpenoids and phenylpropanoids found in essential oils have antioxidant properties as well. These compounds could stabilize free radicals due to the presence of a hydroxyl group (-OH) on a benzene ring in their structure. As a result, they can function as reducing agents and inhibitors of singlet oxygen by moving the hydrogen atom from the OH group to the free radical (Ferreira et al., 2019).

Plant-derived compounds act through distinct yet complementary pathways to mitigate oxidative deterioration in meat. Phenolic acids and flavonoids, such as rosmarinic and gallic acids, primarily intervene at the initiation stage of lipid oxidation by donating hydrogen atoms that neutralize lipid radicals and interrupt chain propagation (Kalogianni et al., 2020; Ferreira et al., 2019). In contrast, phenolic terpenoids and phenylpropanoids, including eugenol, thymol, and carvacrol, are more active during the propagation and termination phases, where their conjugated molecular structures stabilize peroxy radicals and convert hydroperoxides into non-radical, stable species (Al-Mijalli et al., 2023; Pandey et al., 2024). Furthermore, these compounds effectively chelate transition metals such as Fe²⁺ and Cu²⁺ that catalyze Fenton-type reactions, thereby minimizing the formation of secondary oxidation products like malondialdehyde and 4-hydroxynonenal (Domínguez et al., 2019; Geng et al., 2023). Beyond their radical-scavenging and metal-chelating capacities, several polyphenols, especially those present in clove, rosemary, and grape extracts, contribute to maintaining mitochondrial functionality in muscle tissues by preserving membrane potential and reducing reactive oxygen species formation during refrigerated storage (Ahmed et al., 2022; Horbańczuk et al., 2019; Mutlu and Mor, 2025). By stabilizing mitochondrial membranes, these bioactives attenuate oxidative stress cascades that typically accelerate lipid peroxidation and pigment degradation, thereby improving both the oxidative stability and sensory quality of stored meat products (Wu et al., 2022; Domínguez et al., 2021). The antioxidant performance of plant-derived compounds is tightly linked to their phenolic profile and to how these molecules distribute within and interact with the meat matrix. Hydrophilic phenolics (e.g., caffeic and gallic acids) preferentially reside in aqueous domains, where they efficiently quench reactive species and help limit protein oxidation (including carbonyl formation). In contrast, more lipophilic phenolics such as eugenol, carvacrol and thymol partition into lipid-rich regions, interrupting lipid-peroxidation chains and stabilizing nearby membranes (Efenberger-Szmechtyk et al., 2021; Diniz do Nascimento et al., 2020). Structure-activity relationships also matter: additional hydroxyl/methoxy groups facilitate resonance-stabilization of the phenoxyl radical, which helps explain the stronger antioxidant capacity seen in polyhydroxylated flavonoid-rich extracts (Ferreira et al., 2019). Beyond redox chemistry, polyphenols can bind myofibrillar proteins via hydrogen bonding and hydrophobic contacts, reinforcing muscle ultrastructure and slowing downstream oxidative deterioration (Domínguez et al., 2019; Ozdal et al., 2013). Functionally, this creates a diffusion-limiting, protective interface that reduces oxygen and reactive species access to lipid and protein targets, helping preserve texture and colour during storage. Together, these links between composition, activity, and microstructure provide a coherent mechanism for how plant extracts enhance meat preservation (Figure 3).

5 Selected plant extracts and their essential oils for preservation of meat and meat products

In literature, numerous plant extracts and essential oils were investigated and suggested as promising source of meat products preservation (Tables 1, 2; Figure 4).

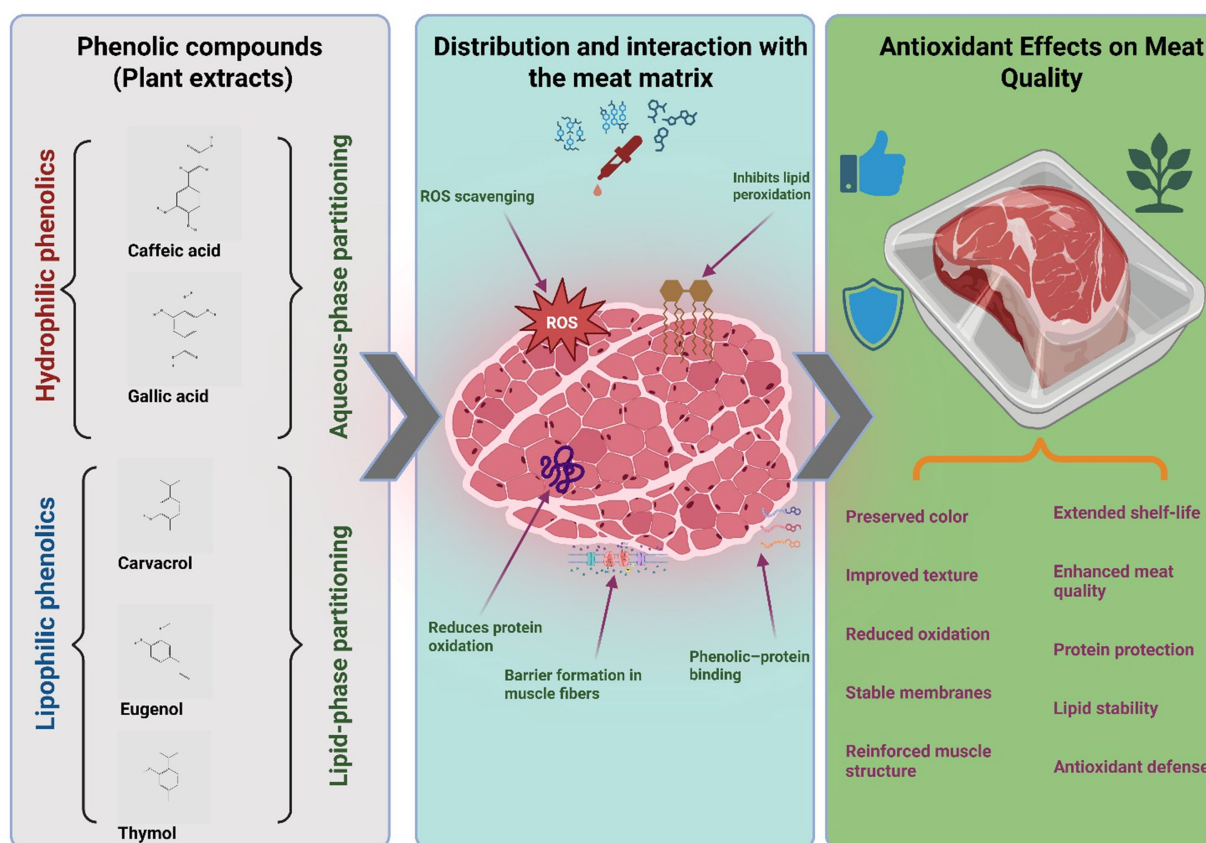


FIGURE 3

Antioxidant mechanisms of some plant phenolics in the meat matrix. Hydrophilic phenolics like caffeic and gallic acids neutralize reactive species in watery areas, protecting proteins. Lipophilic ones such as eugenol and thymol act in fatty regions, halting lipid oxidation and stabilizing membranes. Together, they strengthen muscle tissue structure and preserve meat color and texture during storage. (This figure was created by the author using BioRender).

5.1 Green tea leaf extracts and essential oil

Green tea (*Camellia sinensis*) has attracted significant attention as a natural preservative for meat products, primarily due to its high content of polyphenols such as catechins, which exhibit both antioxidant and antimicrobial properties (Cioanca et al., 2024). Catechins, together with tannins and L-theanine, not only inhibit lipid oxidation and microbial growth but also contribute to flavour attributes, such as umami taste and protein-tannin interactions, which can alter the physicochemical characteristics of food (Han et al., 2024). This dual role makes green tea extract (GTE) particularly relevant for clean-label preservation strategies.

Several studies confirm its strong antioxidant potential. Passos et al. (2022) reported that the addition of 0.5% GTE to chicken patties reduced lipid oxidation and discoloration while maintaining acceptable sensory properties. Similarly, Pateiro et al. (2014) found that pig pâtés treated with GTE and grape seed extract exhibited lower TBARS values and fewer lipid-derived volatiles than samples treated with synthetic BHT, suggesting that natural antioxidants can match or surpass synthetic ones in protecting meat quality. Alnori et al. (2022) also demonstrated that minced mutton enriched with GTE showed improved pH stability, higher myoglobin content, and reduced drip losses, further supporting its role in quality preservation.

However, the antimicrobial efficacy of green tea extract is variable. While methanolic extracts and essential oils of green tea have inhibited a broad spectrum of pathogens, including *Salmonella Typhimurium*, *Listeria monocytogenes*, *Campylobacter jejuni*, and *E. coli* (Salih et al., 2024; Alirezalu et al., 2017), effective concentrations can be relatively high, raising concerns about potential impacts on sensory attributes. In this respect, in most reported meat systems, green tea may not match the consistent antimicrobial performance of oregano or clove oils, which contain more potent phenolic volatiles. Nevertheless, its advantage lies in consumer acceptance: unlike pungent oils, GTE imparts a mild and often desirable taste profile, reducing the risk of rejection in meat products (Chang et al., 2017; Fadji et al., 2023).

Innovative applications have further expanded its potential. Borzi et al. (2019) demonstrated that incorporating GTE into active packaging extended the shelf life of minced meat up to 23 days, while Chen et al. (2019) reported that dietary supplementation of green tea powder in broilers improved meat color stability and promoted beneficial microbiota, suggesting roles that extend beyond post-harvest preservation. Moreover, green tea essential oil, though less studied than the extract, has shown promising antioxidant activity and significant antimicrobial effects against common meatborne pathogens (Demir, 2021; Horbańczuk et al., 2019).

TABLE 1 Selected plant extracts used for meat preservation.

No.	Source of extract	Meat product	Concentration	Function and benefits	Limitations/ application	Reference
1	Green tea	Minced mutton	0.5–2%	Strong antioxidant; reduces thiobarbituric acid reactive substances (TBARS); improves color stability, pH, and drip loss; enhances overall quality during chilled storage	Slight tea-like flavor at higher doses; antimicrobial effect moderate	Alnori et al. (2022)
2	Curry leaves and fenugreek leaves	Raw chicken patties	2%	Significantly reduces TBARS values and retards lipid oxidation during refrigerated storage; water extracts act as natural antioxidants in poultry meat	Study evaluated mainly oxidative stability (TBARS); no sensory or microbiological data reported	Devatkal et al. (2012)
3	Unripe papaya	Beef kabab	3.0 mg/100 g	Protein stabilization; improves texture	Limited antimicrobial activity	Saeed et al. (2017)
4	Sage	Pork	0.4–1.0 µL/g	Inhibits <i>E. coli</i> ; extends shelf life	Strong herbal aroma	Danilović et al. (2021)
5	Cinnamon	Sausage	0.3 g/kg	Reduces biogenic amines and bacterial counts; antimicrobial and antioxidant	Strong flavor; solubility in matrix	Sun et al. (2018)
6	Olive leaves	Sausage	500 ppm	Reduces yeasts, molds, total bacterial count; enhances shelf life	Extraction variability; cost	Alirezalu et al. (2019)
7	Banana peel	Chicken meat	5–10%	Reduces Gram-negative and Gram-positive bacteria; low-cost byproduct	High concentration may affect taste	Shaukat et al. (2023)
8	Grape seed	Pork	0.5%	Decreases lipid oxidation; color stabilizer	Limited antimicrobial effect	Xiong et al. (2020b)
9	Papaya leaves	Chicken breast	2%	Antimicrobial and antioxidant in chitosan-gelatin coating; shelf-life extension	Requires coating technology	Hassan et al. (2022)

In summary, green tea is best regarded as a multi-functional preservative with strong antioxidant and moderate antimicrobial capacity, complemented by good consumer acceptance and added nutritional appeal. Its main limitation lies in the variability of antimicrobial efficacy and the relatively high concentrations sometimes required. Future strategies should explore synergistic use with stronger antimicrobials (e.g., oregano or clove oils) and encapsulation or active packaging systems to maximize stability while minimizing sensory impact.

5.2 Rosemary extracts and essential oil

Rosemary (*Rosmarinus officinalis* L., family Lamiaceae) is one of the most extensively studied medicinal plants for meat preservation. Its effectiveness is primarily associated with phenolic diterpenes such as carnosic acid and rosmarinic acid, which exhibit strong antioxidant activity. Rosemary extracts (RE) significantly delay lipid oxidation, a major pathway of meat spoilage that leads to rancidity, off-flavors, discoloration, and loss of nutritional quality ([Rashidaie Abandansarie](#)

TABLE 2 Selected essential oils used for meat preservation.

No.	Source of essential oil	Meat product	Concentration	Function and benefits	Limitations/application	Reference
1	Black cumin	Chicken meat	1%	Inhibits <i>S. aureus</i> and <i>E. coli</i> ; broad-spectrum antimicrobial	Strong aroma; flavor impact	Shahvandari et al. (2021)
2	Cinnamon	Sausage	0.5%	Reduces lipid oxidation, microbial load, biogenic amines; dual antioxidant and antimicrobial	Strong flavor; cost considerations	Zhang et al. (2019)
		Minced beef	1.2% (v/v)	Inhibits Gram-positive bacteria <10 ⁶ CFU/g; effective antimicrobial	Flavor intensity; solubility issues	Yitbarek et al. (2023)
3	Lemon	Chicken breast	0.2–0.5%	Inhibits <i>Pseudomonas</i> spp. and lactic acid bacteria; mild flavor	Limited antimicrobial spectrum	Hosseini et al. (2021)
4	Clove	Ground beef	0.5–5%	Inhibits Gram-positive and Gram-negative bacteria; prolongs shelf life	Strong flavor; dosage optimization required	Pateiro et al. (2021b)
5	Shirazi thyme	Ground beef	6%	Inhibits lipid oxidation; potent antioxidant	High concentration affects flavor; cost	Amiri et al. (2019)
6	Rosemary	Beef	4%	Inhibits <i>Pseudomonas</i> spp., <i>Brochothrix thermosphacta</i> , Enterobacteriaceae; well-studied	Strong herbal aroma; high concentration	Sirocchi et al. (2017)
7	Cinnamon	Ground beef	5%	Inhibits <i>Listeria monocytogenes</i> ; strong antimicrobial	High concentration; flavor issues	Khaleque et al. (2016)
8	Sage	Minced pork	0.4–0.6 μ L/g	Inhibits <i>E. coli</i> ; effective natural antimicrobial	Strong aroma; microdosing needed	Danilović et al. (2021)
9	Thyme	Beef sausage	2.69%	Antioxidant and antimicrobial; prolongs shelf life	Herbal taste; cost considerations	Sedki et al. (2020)

et al., 2019; Resendiz-Cruz et al., 2021). By scavenging free radicals and interrupting chain reactions catalyzed by transition metals, RE reduces the formation of hydroperoxides and secondary oxidation products such as aldehydes and ketones. For example, Al-Hijazeen and Al-Rawashdeh (2017) reported that ground chicken meat treated with RE (350 ppm) showed significantly lower TBARS values and improved sensory stability compared to controls. Similarly, Feng et al. (2016) demonstrated that RE combined with ϵ -polylysine effectively suppressed lipid oxidation in chicken breast during 10 days of refrigerated storage.

While rosemary extracts are excellent antioxidants, their antimicrobial activity is generally weaker than that of essential oils rich in volatile phenolics such as oregano (carvacrol, thymol) or clove (eugenol). This often requires higher concentrations of RE to achieve microbial inhibition, which may raise sensory concerns. In contrast, rosemary essential oil (REO), which contains monoterpenes such as 1,8-cineole, α -pinene, and camphor, exhibits broader antimicrobial effects. Olivas-Méndez et al. (2022) showed that 1% REO inhibited the growth of *Staphylococcus aureus*,

Salmonella spp., molds, yeasts, lactic acid bacteria, and coliforms in beef hamburgers and minced meat, while also enhancing sensory attributes such as color, aroma, and flavor. Śmiecińska et al. (2024) further demonstrated that combining REO with vacuum packaging delayed lipid oxidation and extended the shelf life of minced pork up to 14 days. Importantly, rosemary is already a familiar culinary herb in meat preparation, which increases consumer acceptance compared to oils with stronger, less familiar aromas such as oregano or clove.

Recent advances in delivery systems have further enhanced the application of REO. For instance, Mutlu and Mor (2025) developed multilayer chitosan films enriched with rosemary oil nanoemulsions (0.5–1.5%), which significantly delayed microbial growth and lipid oxidation in minced beef. Films with 1.5% REO nanoemulsion were particularly effective against spoilage bacteria, although differences diminished at longer storage times. Similarly, coatings incorporating REO applied to chicken breasts not only improved microbiological stability but also received favorable sensory evaluations (Marc et al., 2022).

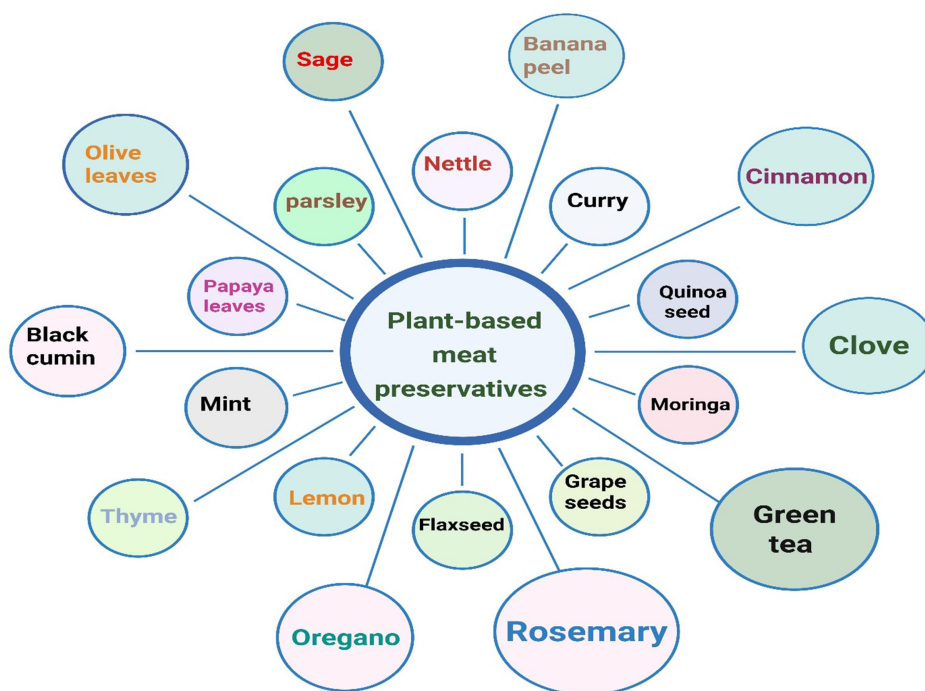


FIGURE 4

Spectrum of plant-derived compounds with potential as natural preservatives in meat and meat products. This figure illustrates a non-exhaustive selection of plant - based meat preservatives investigated for their efficacy in inhibiting meat spoilage and ensuring safety. These natural sources are rich in bioactive compounds, such as polyphenols, flavonoids, terpenes, and essential oils, which exhibit potent antimicrobial and antioxidant properties. Their application aims to control pathogenic and spoilage microorganisms in meat, retard lipid oxidation, and maintain sensory quality, thereby serving as a natural alternative or complement to synthetic preservatives in response to growing consumer demand for clean-label products. (This figure was created by the author using BioRender).

In summary, rosemary should be considered a powerful natural antioxidant with moderate antimicrobial potential. Its main competitive advantage lies in its sensory acceptability, as consumers are already accustomed to its flavor in meat products. However, its relatively weaker antimicrobial efficacy compared to other essential oils suggests that future applications should focus on synergistic combinations (e.g., REO with oregano or clove oils) and advanced encapsulation or controlled-release systems to achieve microbial safety while maintaining desirable sensory properties.

5.3 Grape extracts and essential oil

Grapes and their by-products (seeds, skins, pomace, and wine residues) represent a valuable source of bioactive compounds, particularly polyphenols such as catechins, epicatechin, procyanidins, and gallic derivatives (Padilla-González et al., 2022; Sirohi et al., 2020). Grape seed extract (GSE) has consistently shown strong antioxidant activity, effectively scavenging free radicals and inhibiting lipid oxidation, one of the primary causes of meat spoilage (Reddy et al., 2013). Several studies demonstrated its capacity to preserve meat quality: GSE delayed lipid oxidation and improved microbiological stability in beef (Horbańczuk et al., 2019), chicken patties (Nardoia et al., 2017), and minced beef (Amin and Edris, 2017). In addition to oxidative stability, grape polyphenols can also inhibit bacterial growth, with notable effects against *Escherichia coli* and *Listeria monocytogenes* (Zhu et al., 2015).

One distinctive advantage of GSE is its positive impact on sensory attributes. By protecting myoglobin and other pigments from oxidation, it helps maintain the characteristic red color of meat, while its phenolics contribute to flavor stability (Munekata et al., 2020). This contrasts with some essential oils, such as oregano or clove, which may present sensory challenges due to their strong aroma. Grape-derived compounds are generally milder in flavor, which supports consumer acceptance in clean-label formulations.

Despite these strengths, the antimicrobial potency of GSE is not as pronounced as that of essential oils rich in volatile phenolics (e.g., oregano or thyme). High concentrations are often required to achieve comparable microbial inhibition, which may increase costs and pose formulation challenges. Nevertheless, combining GSE with other extracts can produce synergistic effects. For example, Pateiro et al. (2014) reported that pâtés treated with GSE or green tea extract showed superior oxidative stability compared to BHT, and the combination of natural extracts further reduced lipid-derived volatiles, underscoring the potential of multi-extract approaches. Grape seed oil has also emerged as a promising preservative due to its high content of flavonoids and tannins (Zhou et al., 2022). These compounds improved both antioxidant and antimicrobial activities, slowing down lipid oxidation and microbial proliferation in meat (Olvera-Aguirre et al., 2023). However, the stability of grape seed oil during processing and storage remains a challenge, given its susceptibility to oxidation.

In summary, grape-derived extracts and oils are best characterized as mild but effective antioxidants with added sensory

and nutritional benefits. Their relatively lower antimicrobial strength compared to more pungent essential oils is balanced by better consumer acceptance and compatibility with meat flavor. Future research should focus on synergistic formulations (e.g., GSE + oregano oil) and encapsulation technologies to stabilize grape bioactives and enhance their antimicrobial potential, while simultaneously valorizing winemaking by-products in a sustainable preservation strategy.

5.4 Oregano extract and essential oil

Oregano (*Origanum vulgare*) is one of the most widely investigated plant sources for meat preservation, primarily due to its high content of phenolic compounds such as carvacrol and thymol, which exhibit both strong antimicrobial and antioxidant activity (Leyva-López et al., 2017). Oregano extracts (OE) effectively inhibit spoilage and pathogenic microorganisms, including *Escherichia coli* and *Salmonella* spp., thereby extending shelf life of the meat and preventing food poisoning (Pavli et al., 2019). In addition, OE reduces lipid oxidation in meat, preventing rancidity and loss of nutritional quality (Angelovičová et al., 2021). Unlike milder extracts such as grape seed or green tea, oregano is widely regarded in the literature as a “powerhouse antimicrobial,” with consistently strong efficacy against both Gram-positive and Gram-negative bacteria.

Oregano essential oil (OEO) has attracted particular attention for its preservative capacity in meat and other foods. Several studies have shown that OEO effectively suppresses the growth of key pathogens, including *Salmonella*, *E. coli*, and *Listeria monocytogenes* (Chang et al., 2017; Kwon et al., 2017; Xiong et al., 2020a; Fadji et al., 2023). Its antioxidant activity further reduces lipid and protein oxidation, contributing to improved storage stability and extended shelf life. In some cases, OEO at concentrations of 100–150 ppm performed comparably to synthetic preservatives such as ascorbate (E-300), nitrite (E-250), and BHA in ground meat systems (Al-Hijazeen, 2019). These results highlight OEO as one of the most promising natural alternatives for replacing synthetic additives in meat processing.

However, the major challenge of OEO lies in its intense aroma and flavor, which can overpower the natural taste of meat if not carefully controlled. This sensory limitation differentiates oregano from rosemary or grape extracts, which are better tolerated by consumers. Recent advances in delivery systems aim to address this challenge: OEO incorporated into active films significantly reduced microbial growth in beef (Gaba et al., 2022), while pectin-based coatings with OEO and resveratrol nanoemulsion extended the shelf life of pork meat to 20 days at 4 °C, keeping microbial counts below the spoilage threshold and maintaining lower malondialdehyde levels (Xiong et al., 2020a). These approaches highlight the role of encapsulation and edible coatings in enhancing OEO functionality while mitigating sensory drawbacks.

In summary, oregano is best characterized as a potent antimicrobial with complementary antioxidant activity, making it particularly effective against a broad spectrum of meatborne pathogens. Its main limitation remains its strong flavor profile, which may restrict direct application at effective antimicrobial doses. To unlock its full potential, future research should emphasize controlled-release systems, nanoencapsulation, and synergistic formulations (e.g., combining OEO with milder antioxidants

like rosemary or grape seed extract) that reduce the required concentration while maintaining efficacy and consumer acceptance.

5.5 Cinnamon extract and essential oil

Cinnamon (*Cinnamomum* spp.) has been widely investigated as a natural preservative due to its strong antimicrobial and antioxidant activities (Liu et al., 2024). Its bioactivity is mainly attributed to cinnamaldehyde and other phenolic compounds, which disrupt bacterial membranes, interfere with enzymatic activity, and scavenge reactive oxygen species (Vasconcelos et al., 2018; Chai et al., 2022). Cinnamon extract (CE) has been shown to inhibit microbial growth and improve oxidative stability in meat, thereby enhancing shelf life and sensory attributes (Zawani et al., 2022; Hussain et al., 2021; Shu et al., 2024).

Cinnamon essential oil (CEO) demonstrates particularly strong antimicrobial potential. Studies report its effectiveness against major foodborne pathogens such as *Salmonella* spp., *Escherichia coli*, and *Listeria monocytogenes* (Gheorghe-Irimia et al., 2024; Jaramillo Jimenez et al., 2024). Its phenolic constituents, especially cinnamaldehyde, exhibit a dual action by disrupting microbial membranes and inhibiting metabolic enzymes (Didehdar et al., 2022). Collectively, these studies position CEO as one of the more potent antimicrobial essential oils investigated in meat systems, with efficacy often comparable to oregano oil at similar concentrations, albeit with a different sensory profile. Beyond antimicrobial activity, cinnamon extracts and oils are also strong antioxidants. Their radical-scavenging capacity (hydroxyl and DPPH radicals) has been well documented (Reddy et al., 2018; Diniz do Nascimento et al., 2020). In practical applications, CEO lowered TBARS values in ground beef during 10 days of cold storage (Horbańczuk et al., 2019), while CEO microcapsules at 0.5–1% (w/v) successfully inhibited both lipid oxidation and microbial growth in meat. These findings highlight the potential of encapsulation systems to enhance stability and efficacy, while also allowing lower effective concentrations.

Interestingly, cinnamon supplementation in poultry diets has been reported to reduce cholesterol levels in broiler meat and improve overall quality (Gomathi et al., 2018), suggesting that cinnamon can contribute to meat preservation not only at the post-processing stage but also through animal feeding strategies. However, the strong and distinctive flavor of cinnamon may limit its direct application in some meat products, particularly when high doses are required. Compared with rosemary or grape seed, cinnamon has superior antimicrobial potency but poses greater sensory challenges.

In summary, cinnamon extracts and essential oils are best regarded as potent antimicrobial and antioxidant agents with versatile applications in meat preservation. Their strong activity against both spoilage and pathogenic microorganisms, combined with effective control of lipid oxidation, make them promising candidates to replace or reduce synthetic additives. Future applications should focus on encapsulation, nanoemulsion, and synergistic combinations to mitigate sensory issues and improve stability, thereby maximizing their industrial applicability.

5.6 Flaxseed extract and essential oil

Flaxseed (*Linum usitatissimum*) has received increasing attention in meat preservation due to its rich composition of bioactive

compounds, including lignans, polysaccharides, and high levels of polyunsaturated fatty acids (PUFAs), particularly α -linolenic acid (Mueed et al., 2024). Flaxseed extract (FSE) exhibits notable antioxidant properties, effectively reducing lipid oxidation—the primary cause of rancidity and quality deterioration in meat (Waszkowiak and Rudzińska, 2014; Suleman et al., 2025). Beyond extracts, flaxseed essential oil (FEO) also demonstrates strong antioxidant activity, contributing to delayed lipid peroxidation and extended shelf life in meat products (Mueed et al., 2025).

An additional advantage of flaxseed compared with other plant-derived preservatives is its nutritional enrichment potential. Incorporation of flaxseed oil not only contributes to oxidative stability but also enhances the nutritional profile of meat by increasing omega-3 PUFA content (Ali et al., 2023). This dual functionality positions flaxseed as both a preservative and a dietary supplement. Indeed, formulations of bologna-type sausages for older adults enriched with flaxseed improved fatty acid profiles while maintaining acceptable sensory properties (Reyes-Padilla et al., 2018). Similarly, the partial replacement of beef in patties with flaxseed and tomato paste (up to 20%) reduced cholesterol and saturated fat content while increasing PUFA levels (Valenzuela-Melendres et al., 2018). Such results underline its value not only for preservation but also for functional meat product development.

Flaxseed oil has also been reported to display antibacterial effects, suppressing spoilage microorganisms and pathogens (Wang et al., 2024). However, its antimicrobial potency is generally weaker than that of essential oils rich in volatile phenolics such as oregano or cinnamon in most reported meat-model studies, meaning that higher doses or combination strategies may be required (Wang et al., 2024; Liu et al., 2024). In summary, flaxseed extracts and oils are best characterized as dual-function agents that provide both preservation and nutritional enhancement. While their antioxidant capacity is strong, their antimicrobial efficacy is more limited, and their own oxidative instability poses formulation challenges. Future work should focus on stabilization techniques (e.g., microencapsulation, nanoemulsion) and synergistic blends with stronger antimicrobials to fully exploit flaxseed's potential as a clean-label preservative and functional ingredient in meat products.

5.7 Clove extracts and essential oil

Clove extract has garnered considerable attention in food science as a natural preservative, largely due to its rich composition of phenolic compounds, including eugenol, eugenyl acetate, and caryophyllene, which confer strong antioxidant properties (Abdul Aziz et al., 2023; Gengatharan and Abd Rahim, 2023). Compared with other plant extracts, cloves demonstrate notable efficacy in scavenging free radicals, suggesting potential benefits not only for food preservation but also for human health by mitigating oxidative stress-related chronic diseases. This dual functionality positions clove extract as a promising candidate for incorporation into functional foods and active packaging systems (Siddiqui et al., 2023; Tomić et al., 2023).

Beyond antioxidant activity, clove-derived compounds, particularly eugenol, exhibit significant antimicrobial effects, inhibiting both spoilage and pathogenic bacteria (Pandey et al., 2024; Lee et al., 2024). Comparative studies in meat systems indicate that clove extract and essential oil can reduce microbial loads, delay lipid

oxidation, and maintain color and sensory quality, thereby extending shelf life more effectively than some conventional synthetic preservatives (Venkatachalam and Lekjing, 2020; Ahmed et al., 2022; Zahid et al., 2020). Clove essential oil, extracted from clove buds, similarly demonstrates broad-spectrum antimicrobial activity and antioxidant properties, reinforcing its potential as a natural alternative for meat preservation (Al-Mijalli et al., 2023; Haro-González et al., 2021; Wang et al., 2023).

Despite these advantages, challenges remain for industrial application. The strong flavour of clove extracts may impact product acceptability, requiring optimization of concentration and delivery methods. Additionally, variability in bioactive content depending on extraction method and plant origin can affect efficacy (Santesteban-López et al., 2022). Nevertheless, integrating clove-based preservatives offers clear benefits for the meat industry, including reduced reliance on synthetic chemicals, alignment with consumer demand for clean-label products, and enhanced safety and shelf life of perishable foods (Karnwal and Malik, 2024). Future research should focus on standardization, sensory optimization, and synergistic formulations with other natural preservatives to maximize both functionality and consumer acceptance.

5.8 Thyme extract and essential oil

Thyme (*Thymus vulgaris* L.), a member of the Lamiaceae family, is among the most extensively investigated aromatic plants in meat preservation. Its essential oil (TEO) is particularly rich in phenolic monoterpenes such as thymol and carvacrol, which are largely responsible for its strong antimicrobial and antioxidant properties (Angane et al., 2022). These compounds disrupt bacterial membranes, destabilize proton gradients, inhibit ATP synthesis, and interfere with enzyme systems essential for microbial survival. As a result, TEO demonstrates broad-spectrum inhibition against key meatborne pathogens including *Salmonella* spp., *Listeria monocytogenes*, *Escherichia coli*, and *Staphylococcus aureus* (De Rossi et al., 2025; Efenberger-Szmecnyk et al., 2021).

Several meat-model studies support its potency. Sedki et al. (2020) reported that thyme essential oil (2.69%) significantly reduced lipid oxidation (TBARS) and microbial growth in beef sausages during refrigerated storage, extending shelf life by up to 10 days compared with untreated controls. Similarly, Hosseini et al. (2021) observed marked reductions in *Pseudomonas* and lactic acid bacteria counts when TEO was applied to poultry meat, highlighting its dual antimicrobial and antioxidant functionality.

Beyond microbiological control, thymol and carvacrol act as effective radical-scavenging and metal-chelating agents, slowing the formation of primary and secondary lipid oxidation products. This results in improved colour stability, reduced rancidity, and maintenance of sensory quality throughout storage. Compared with rosemary or grape seed extracts, thyme oil shows stronger antimicrobial activity but may impart a more dominant herbal flavor at higher concentrations. Encapsulation technologies such as nanoemulsions, liposomes, and chitosan films have therefore been increasingly utilized to improve stability, enhance antimicrobial efficacy, and minimize sensory impact.

Therefore, thyme essential oil is a high-performance natural preservative with strong scientific evidence supporting its application

in beef, poultry, and processed meat systems. However, sensory control, standardization of thymol/carvacrol ratios, and formulation optimization remain critical for industrial implementation. Future work should focus on synergistic blends, especially with rosemary, oregano, or clove oils, to reduce required dosages and improve multifunctional activity.

6 State-of-the-art plant-derived advances in meat preservation

6.1 Advanced delivery and encapsulation systems

The integration of plant extracts and essential oils (EOs) in meat preservation has evolved beyond simple antioxidant or antimicrobial use, driven by advances in nanotechnology, green chemistry, and controlled delivery systems. Nanoencapsulation enhances the stability, bioactivity, and controlled release of bioactive compounds, while minimizing the sensory impact that often limits their direct application (Boskovic et al., 2019). Various encapsulation methods, such as nanoemulsions, liposomes, solid lipid nanoparticles, and biopolymer-based carriers (e.g., chitosan, zein), have improved the oxidative and microbial stability of meat systems (Shishir et al., 2018; Gali et al., 2023; Kumar et al., 2024).

Nanoemulsions of rosemary, oregano, thyme, or clove oils exhibit enhanced antimicrobial efficacy at lower concentrations, due to increased surface area and better interaction with microbial membranes. Moreover, encapsulated EOs maintain volatile stability and reduce aroma intensity, balancing efficacy and sensory quality. In parallel, ZnO nanoparticles have been explored as antibacterial and nanosensor agents, capable of detecting spoilage and inhibiting microbial proliferation through their unique catalytic and electrical properties (Ulloa-Saavedra et al., 2022).

Edible coatings and films containing natural antioxidants further contribute to shelf-life extension. For example, alginate coatings enriched with rosemary and oregano EOs reduced lipid oxidation in beef steaks by nearly 47% over 14 days, while preserving color and consumer acceptability (Vital et al., 2016). Such systems illustrate how bioactive encapsulation and biopolymer integration can simultaneously enhance safety, quality, and consumer perception of meat products.

6.2 Electrospinning and intelligent packaging

Electrospinning technology has emerged as one of the most promising innovations in active and intelligent packaging. Electrospun nanofibers, produced from biopolymers such as chitosan or gelatine, possess high surface-to-volume ratios and tunable porosity, enabling efficient loading and release of natural antimicrobials and antioxidants (Gagaoua et al., 2022). Incorporating plant extracts, essential oils, or nanomaterials (e.g., silver nanoparticles, polyphenols) into electrospun fibres significantly reduces microbial growth and lipid oxidation in meat products.

Beyond active protection, electrospun fibres serve as the foundation for smart packaging systems that respond to

environmental stimuli such as pH, temperature, or gas emission changes. Colorimetric indicators based on natural pigments, such as anthocyanins from grape skins, can signal freshness by shifting color in response to volatile amines, providing real-time spoilage detection (Forghani et al., 2021). Despite these advances, large-scale commercialization is still constrained by cost, regulatory uncertainty, and reproducibility. Research must focus on optimizing fibre stability, mechanical performance, and sustained-release profiles to ensure industrial applicability (Meraz-Dávila et al., 2021; Jurić et al., 2023).

6.3 Synergistic preservation and green extraction technologies

Combining essential oils and plant extracts with chemical or physical preservation methods has proven effective in overcoming microbial resistance and extending shelf life. The synergy between plant-derived antimicrobials and conventional agents (e.g., organic acids, mild heat, high-pressure processing) enhances both microbiological safety and sensory stability in meat and seafood (Huang et al., 2021). Moreover, the chemical diversity of phenolic compounds from oregano, cinnamon, rosemary, grape, and green tea leads to additive or synergistic antioxidant interactions, depending on concentration ratios, improving both shelf life and sensory acceptance (Khodaei et al., 2023).

Meanwhile, green extraction technologies, including ultrasound-, microwave-, and enzyme-assisted extraction, as well as supercritical fluid extraction, have transformed the production of plant bioactives (Awad et al., 2021). These methods improve yield and purity, minimize solvent use, and preserve thermolabile compounds, aligning with sustainability goals. However, precise identification and purification of active ingredients remain a bottleneck, requiring integration of analytical chemistry and process engineering to ensure consistent industrial performance.

6.4 Emerging concepts: smart monitoring and cell-based meat

The next frontier in natural meat preservation lies in intelligent systems capable of real-time monitoring of freshness and safety. Smart sensors integrated into packaging can detect microbial growth, temperature deviations, or volatile amine formation, offering early warning against spoilage (Ahmed et al., 2018; Sani et al., 2024). Coupled with automation and AI-based data analysis, these systems can transform quality assurance and traceability within meat supply chains.

In parallel, cell-based (cultured) meat represents an emerging innovation in sustainable protein production (Ye et al., 2022). While its large-scale commercialization remains challenging due to production costs, regulatory uncertainty, and consumer acceptance, the integration of natural plant-derived preservatives could enhance its safety, shelf life, and sensory resemblance to conventional meat. Incorporating antioxidant-rich extracts or nano-encapsulated EOs into cultured meat systems could mitigate oxidative stress during growth and post-harvest stages, marking a potential convergence between food biotechnology and natural preservation research.

7 Future perspectives

Future innovations in plant-derived meat preservatives should move beyond simple additive substitution towards fully integrated, technology-driven preservation systems. Advances such as nanoencapsulation, biopolymer coatings, and smart packaging offer controlled release, enhanced stability, and reduced sensory interference, addressing persistent challenges of volatility, poor solubility, and uneven efficacy across different meat matrices (Pateiro et al., 2021a; Maciel et al., 2020). Incorporating consumer acceptability and sensory perspective is vital for the practical implementation of plant-derived antioxidants. Volatile phenolic compounds and essential oils can significantly influence aroma, flavour, and colour perception, sometimes leading to sensory rejection despite strong antioxidant efficacy. Nanoencapsulation and edible biopolymer coatings can effectively mitigate these drawbacks by controlling the release of active compounds, reducing direct contact with muscle tissues, and minimizing undesirable odour or flavour intensity. Such technologies not only enhance consumer acceptance but also maintain product sensory integrity during storage, supporting the development of clean-label meat products that balance functionality with sensory quality.

Integrating circular-economy principles, such as valorising agricultural by-products, tea residues, grape pomace, rosemary leaves, and fruit peels, will further enhance environmental and economic sustainability (Domínguez et al., 2021; Alirezalu et al., 2017). Looking ahead, dynamic and responsive preservation systems capable of maintaining freshness and safety in real time represent the next frontier. Future research should focus on synergistic extract combinations, intelligent packaging responsive to oxidation or spoilage cues, and scalable encapsulation strategies that ensure reproducibility and affordability. Bridging materials engineering, biotechnology, and food science will be crucial to position plant-based preservatives as transformative tools for a cleaner, safer, and more sustainable global meat industry (Pateiro et al., 2021b; Xie et al., 2024).

Despite considerable progress, comparative evaluation of plant-derived antioxidants in meat systems remains hindered by methodological variability. Inconsistent extraction solvents (ethanol, methanol, water, or mixed systems), plant part selection (leaves, seeds, peels), and lack of standardized antioxidant assays (DPPH, FRAP, ORAC, TBARS) continue to generate significant inter-study variability, limiting reproducibility and comparability (Pérez-Palacios and Estévez, 2022; Echegaray et al., 2021). These inconsistencies are further amplified by meat matrix differences, where protein–lipid ratios, water activity, and endogenous antioxidant enzymes affect phenolic compound diffusion and reactivity (Wu et al., 2022). To enhance reproducibility, future research should establish harmonized extraction protocols, ensure consistency in solvent polarity and plant parts used, and standardize antioxidant assessment methodologies across model systems. The incorporation of AI tools is also suggested to further support these efforts.

Incorporating comparative analyses between red and white meat systems will also provide critical biochemical context. Red meats, with their higher myoglobin and heme iron content, exhibit accelerated oxidative discoloration and lipid peroxidation due to iron-catalysed Fenton reactions. Conversely, white meats, characterized by lower myoglobin levels but higher polyunsaturated fatty acid (PUFA) content, show slower pigment oxidation yet greater susceptibility to peroxidative rancidity (Manessis et al., 2020; Ismail and Huda, 2024).

Understanding how phenolic compounds interact with these contrasting biochemical environments, through radical scavenging, metal chelation, and protein binding, is essential for developing matrix-specific antioxidant strategies optimized for each meat type. Ultimately, advancing this field requires a systems-level approach that integrates standardized analytical protocols, innovative delivery technologies, and comparative mechanistic frameworks across red and white meat models. Such efforts will accelerate the transition from descriptive studies toward predictive, technology-enabled preservation science.

8 Conclusion

Plant-derived extracts and essential oils have emerged as credible, science-based alternatives to synthetic preservatives in modern meat systems. Evidence across beef, poultry, and fish products shows that these compounds, rich in phenolics, terpenoids, and flavonoids, can meaningfully slow microbial growth, suppress lipid and protein oxidation, and help maintain desirable color and sensory attributes during storage. Their actions are multifaceted: they disrupt microbial membranes, chelate pro-oxidant metals, quench reactive species, and help stabilize muscle microstructure. Together, these mechanisms position plant-based preservatives as valuable tools for improving both safety and overall quality in perishable meat products. Recent technological developments have strengthened their practical relevance. Encapsulation systems, electrospun fibers, and biopolymer coatings allow controlled release, improved chemical stability, and reduced sensory impact, addressing some of the major obstacles associated with the direct use of volatile essential oils. Intelligent and active packaging approaches further extend shelf life and provide opportunities for real-time quality monitoring. In parallel, green extraction methods and the valorization of by-products such as grape pomace, tea residues, and herb trimmings support sustainability goals and can reduce production costs. Despite these advances, several gaps must be resolved before widespread commercial adoption becomes feasible. Natural variability in plant composition, differences in extraction methods, and the absence of standardized antioxidant and antimicrobial testing protocols continue to produce inconsistent results across studies. Sensory impacts remain a practical limitation, particularly when higher concentrations are required for microbial control. Furthermore, regulatory clarity and cost-effective scale-up processes are still developing globally. Future progress will depend on harmonized analytical approaches, better understanding of how plant phenolics interact with different meat matrices, and strategic use of synergistic combinations. Technologies such as nanoemulsions, edible coatings, and smart packaging will play an increasingly important role in delivering consistent performance while maintaining consumer acceptance. By integrating materials science, food chemistry, and green technologies, plant-derived preservatives can transition from supplemental additives to central components of next-generation preservation strategies.

Author contributions

ME: Conceptualization, Investigation, Methodology, Writing – original draft. AA: Project administration, Resources, Funding

acquisition, Writing – review & editing. EA: Investigation, Project administration, Writing – original draft, Visualization, Validation. GA: Formal analysis, Supervision, Writing – review & editing, Investigation.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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