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EFFECT OF ESSENTIAL OILS IN MEAT

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Abstract
Consumer demand for safer and healthier food products has driven the meat industry to seek natural alternatives to synthetic preservatives. Essential oils (EOs), volatile compounds derived from plants, have emerged as promising natural preservatives due to their strong antimicrobial and antioxidant activities. This review provides a comprehensive analysis of the effectiveness of EOs in extending the shelf life of meat and meat-based products. It discusses the composition and major bioactive compounds such as terpenes, terpenoids, and phenylpropanoids, which play key roles in preservation. Moreover, critical factors influencing EO effectiveness, including concentration, interactions with food matrices, and application methods, such as direct incorporation, vapor-phase diffusion, and encapsulation technologies, are thoroughly examined. The mechanisms of EO action, including disruption of microbial cell membranes, generation of reactive oxygen species (ROS), enzyme inhibition, and DNA damage, are described in detail. The antioxidant activity of EOs is also discussed, including their ability to scavenge free radicals, chelate metals, and deactivate singlet oxygen. This review emphasizes the potential of EOs as natural preservatives that support food safety and quality in line with consumer preferences for clean-label products with minimal synthetic additives.

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Introduction

The global meat market has increased over the past fifty years because of its role as a primary source of animal protein with essential amino acids that are important for the human body [1]. Protein is an integral criterion for the quality of meat and meat products. Meat products are products of further processing of meat derived from muscles and/or animal fat and are produced with the use of additives to improve sensory quality and product volume [2]. Basic technologies in the meat processing industry include curing, seasoning, filling, smoking, cutting, and mixing [2]. Meat is vulnerable to spoilage and has short shelf life due to high nutrient and moisture content with almost neutral pH being a suitable medium for microbial growth [3]. In addition, meat especially with high fat content, is very susceptible to oxidation. This process can reduce the quality of a product by producing an unpleasant aroma, changes in taste, and reduced nutritional value [4]. Lipid oxidation in meat is influenced by various factors, such as light exposure, storage temperature, acidity level, and fatty acid composition. In addition, proteins in meat can also undergo oxidation, which has an impact on color changes and decreased nutritional content [5].

As a result, many meat industries are using chemical preservatives to extend shelf life and avoid deterioration of meat and meat products. These chemical preservatives play a role as antimicrobial agents to inhibit microbial growth, thus maintaining the quality of products. Antimicrobial compounds are commonly used in meat products such as chloride, sulfides, organic acids, nitrites [6,7]. Other chemical preservatives applied in food include butylated hydroxyanisole (BHA) and butylated hydroxyl toluene (BHT) [8]. However, nowadays, the awareness of people about benefits of consuming healthier food is increasing. They tend to prefer natural preservatives compared to chemical preservatives [9]. Furthermore, artificial or chemical preservatives might have adverse effects on consumers' health associated with toxicity effects [10]. Therefore, the use of natural preservatives is more preferred and has been developed in many food industries.

Specifically, the application of herbs, spices, and essential oils in food has been developed over the years. Some studies reported about the effect of essential oils and extracts on food as antioxidants and antimicrobials [11]. Also, plant essential oils have abilities as antiviral and antifungal agents and are regarded as good sources of novel antimicrobial substances [12]. Several studies have been conducted to know the effect of plant essential oils in meat and meat products. Ibrahim et al. [13] studied the use of basil essential oil in minced pork which proved to have a good effect on microbial inhibition and sensory properties. Other plant essential oils that have good potential as preservatives include oregano oil with antibacterial, antifungal, and antioxidant activities [14]; cinnamon oil with antiseptic, antipyretic, and anti-inflammatory activities [15]; garlic oil with the ability to regulate and strengthen the function of the immune system [16]; black pepper oil with anticancer, antifungal, antiseptic and antioxidant activities [17]. Contrary to chemical preservatives, essential oils offer tremendous beneficial effects in food, especially meat and meat products. Given these conditions, a comprehensive study is needed regarding the effectiveness of essential oils as natural preservatives in meat products. Therefore, this review is compiled to examine a degree to which essential oils contribute to extending the shelf life of meat and to understand the mechanism of their active compounds in inhibiting microbial growth and lipid oxidation. A deeper understanding of the preservative potential of essential oils is expected to facilitate the adoption of safer and more sustainable preservation strategies in the food industry, aligning with the growing consumer demand for products with minimum synthetic additives.

Objects and methods

Information was collected from several databases: Scopus, PubMed, ScienceDirect, ResearchGate, and Google Scholar. The keywords used as a search strategy were essential oil, meat, meat product, meat preservation, meat contamination, and oxidation. The information collected from journals was published from 1987 until 2025 (159 references were selected for this review); language: studies published in English. Inclusion criteria were relevance articles on essential oils application, including bioactive compounds, meat and meat products, essential oil mechanism, meat deterioration. Exclusion criteria in this review were unrelated topics: studies not focusing on the application of essential oils on meat and meat products and no access to the full text articles.

Key bioactive compounds in essential oils

Essential oils, also known as volatile or aromatic oils, are concentrated, hydrophobic liquids consisting of volatile aromatic compounds extracted from plants [18]. These oils, often referred to as essences, are complex mixtures of various volatile constituents biosynthesized by living organisms and extracted from the plant matrix through methods such as water, steam, and dry distillation, or mechanical processes like expression in citrus fruits [18,19]. The composition of essential oils is highly variable and is influenced by factors such as plant species, geographical location, and the extraction method used [20]. They are primarily composed of volatile compounds of terpenoid origin, including monoterpenes and sesquiterpenes, which may appear as hydrocarbons or their oxygenated derivatives, such as alcohols, aldehydes, ketones, esters, and phenols. Non-terpenoid compounds such as phenylpropanoids and fatty acids also contribute to the complexity of essential oils [20].

Essential oils (EOs) are concentrated liquids containing volatile compounds extracted from various plant parts, such as flowers, leaves, seeds, bark, and roots — using specific extraction techniques, with steam distillation being the most common method due to its ability to preserve volatile constituents [21,22]. In plants, EOs play essential roles in aroma production, communication, and defense mechanisms [21], while industrially they are widely utilized in medicine, cosmetics, perfumery, and the food industry because of their diverse biological activities, including antioxidant, antimicrobial, anti-inflammatory, anticancer, and antiallergic properties [23,24]. Their lipophilic nature and small molecular size allow EOs to penetrate biological membranes easily, enabling them to exert various therapeutic effects [21].

The bioactivity of essential oils is primarily attributed to the presence of specific organic compounds, including terpenes, terpenoids, phenylpropanoids, and others. There are several key bioactive compounds in EOs:

- **Terpenes and Terpenoids:** These are the most prevalent bioactive compounds in essential oils. They include a variety of structures that impart diverse biological activities such as antimicrobial, anti-inflammatory, and antioxidant properties. Some well-known terpenes include limonene, α-pinene, and thymol [23,24];
- **Phenylpropanoids:** These compounds have been recognized for their anticancer potential. Compounds such as eugenol and geranyl acetate are notable for their antioxidative and antimicrobial properties, making them significant in both therapeutic and food preservation contexts [25,26];
- **Thymol:** Found in many essential oils, thymol exhibits multiple bioactivities, including anti-inflammatory effects. It acts by modulating molecular pathways such as NF-κB and JAK/STAT, and also shows potential in therapeutic formulations due to its antimicrobial powers [27].

Bioactive compounds encompass a wide array of secondary metabolites synthesized by plants and other organisms beyond just the commonly recognized few. While it is common to discuss primary bioactive compounds such as flavonoids, phenolic acids, and carotenoids, there are many more diverse types of bioactive compounds found in various sources. For example, guava leaves are rich in a range of bioactive compounds including tannins, terpenes, alkaloids, and others, which exhibit significant synergistic effects in enzyme inhibition, as well as antimicrobial and anti-inflammatory activities [28]. Ficus fruits also contain a diverse range of biologically active compounds such as carotenoids, flavonoids, phenols, and vitamin C, contributing to their functional properties and health impacts [29].

Moreover, the secondary metabolites derived from *Fomitopsis betulina*, which include terpenoids, phenols, and other classes, exhibit pharmacological activities such as anti-cancer, anti-inflammatory, antimicrobial, antiviral, and anti-malarial effects [30]. Additionally, compounds from marine organisms identified over a span of several decades amount to thousands of chemical substances, highlighting the extensive variety inherent in marine bioactive compounds [31]. In agricultural by-products and plants, various bioactive compounds such as flavonoids, phenolic acids, and α- and β-acids are identified, indicating that the range of bioactive constituents extends well beyond the commonly referenced trio of polyphenols, terpenoids, and alkaloids [32].

There are several applications and benefits of EOs:

— **Food Preservation:** Essential oils are increasingly being used as natural additives for extending the shelf-life of food products. Due to their potent antibacterial and antioxidant properties, they serve as a natural alternative to synthetic preservatives. Composite films incorporating EOs enhance the phenolic stability and shelf-life of food items [33,34];

— **Biotechnological and Industrial Uses:** Essential oils possess characteristics that make them useful in bioactive films and packaging materials, offering a dual role in preservation and environmental sustainability. For example, films made with oregano essential oil have shown high antimicrobial activity, suggesting potential in smart packaging solutions [35].

— **Medicinal Uses:** Essential oils have traditional uses in medicine, supported by scientific findings of bioactive properties like anti-inflammatory, anticancer, and more. They are explored for various therapeutic applications in pharmaceuticals and other health-related fields [24,26].

Factors influencing the effectiveness of essential oils

The efficacy of essential oils (EOs) as preservatives in meat products is modulated by several key factors. In particular, the concentration of the oil used, the composition of the food matrix, and the mode of application all play critical roles in determining antimicrobial and antioxidant outcomes. Below, we review how each of these factors can influence the effectiveness of EOs in meat systems.

Concentration and dosage

The concentration of EOs necessary to inhibit pathogens is a critical factor in their antimicrobial effectiveness. The minimum inhibitory concentration (MIC) of an EO against foodborne microorganisms serves as a baseline for its potency [36]. MIC assays, such as broth dilution methods, identify the lowest concentration that prevents microbial growth in vitro, which informs the dosage for preservative effects. However, translating MIC values from laboratory settings to real food systems is not easy, as studies indicate that EOs effective in vitro may require higher concentrations in actual meat products due to the complex meat matrix and storage conditions that can reduce EO activity [37].

Moreover, EOs are potent flavor agents, and their concentrations can significantly affect the sensory attributes of meat. Even at sub-inhibitory levels, EOs can impart distinct aromas and tastes, but higher concentrations near the MIC can negatively impact consumer acceptability [37]. For example, adding approximately 1.5 % (w/w) of clove or lemongrass oil to ground beef, close to the MIC for *Listeria*, led to a significant decrease in sensory scores for taste and overall acceptability [38]. Concentrations above 3 % were deemed unacceptable in terms of flavor and caused noticeable color changes [38]. This highlights the challenge of balancing antimicrobial efficacy with flavor, as excessive EO can lead to off-flavors and odors perceived as spoilage [37]. Therefore, producers must identify the lowest effective EO dose that inhibits pathogens while remaining below sensory detection thresholds. Combining EOs with other preservation methods, such as mild heating or acids, can help achieve microbial control while minimizing sensory impact [37].

Interaction with food components

The performance of EOs in meat products is significantly influenced by the composition of meat, particularly its fat, protein, and moisture content. EOs, being hydrophobic, tend to partition into lipid-rich phases. This leads to reduced concentrations of active compounds in high-fat meats, which can bind or absorb EOs, diminishing their bioavailability and requiring higher initial doses for antimicrobial effects [36]. Conversely, higher moisture content facilitates EO dispersion and enhances contact with microbes [36].

This phenomenon has been observed in various food systems, such as the reduced antibacterial activity of cinnamon and clove oils against *Listeria* in whole milk due to milk fat binding, while these oils were more effective in skim milk [36]. Similarly, EOs inhibited bacteria more effectively in low-fat cheese compared to full-fat cheese [36]. Essential oils require some moisture to diffuse and contact microbes, indicating that very low-moisture conditions can limit their effectiveness. The fat-protein matrix of meat can act as a sink for lipophilic EO compounds, reducing their active portion, while the water phase is crucial for their antimicrobial and antioxidant functions. Therefore, producers must consider the specific meat composition, as a high-fat sausage may need more EO or different delivery methods than a low-fat product to achieve similar preservative effects [36].

Additionally, the food matrix impacts the antioxidant efficacy of EOs. While many EOs can slow lipid oxidation in meats, their effectiveness depends on their distribution in the lipid phase. If EOs are tightly bound to proteins or trapped away from fats, their ability to scavenge free radicals is reduced. However, if EOs dissolve preferentially in fat, they can protect it from oxidation, provided they remain stable and well-dispersed. High water activity can promote uniform EO dispersion and potentially generate oil-in-water microemulsions that carry antioxidants to lipid oxidation sites. Thus, the intrinsic properties of meat and their interactions with EO compounds are critical for the efficacy of EOs as preservatives [36]. Successful EO application often requires tailoring formulations to the specific food matrix or employing strategies to mitigate matrix binding effects.

Mode of application

The application of essential oils (EOs) to meat products significantly influences their effectiveness and practicality, with two common methods: direct incorporation and vapor-phase diffusion. Direct incorporation involves mixing the EO with meat or adding it to marinades, casings, or edible coatings, ensuring immediate proximity to spoilage or pathogenic microbes. This method can inhibit microbial growth and oxidative spoilage but may lead to rapid loss of volatile compounds and undesirable flavor profiles, particularly in mildly flavored meats [39]. Additionally, some EOs may react with meat components during processing, potentially reducing their effectiveness.

In contrast, vapor-phase application introduces an EO as a volatile vapor in the packaging environment, allowing for diffusion onto the meat surface without complete absorption. This method can be achieved through impregnated packaging materials, EO-infused sachets, or active coatings that release the oil slowly. Vapor-phase application provides uniform surface coverage, effectively targeting surface-growing molds or bacteria [36,40]. It also minimizes sensory impact on the meat. Exposing refrigerated chicken breasts to EO vapors significantly slowed microbial growth and lipid oxidation without detectable sensory changes [41]. However, vapor-phase methods are generally more effective against surface contamination and may not address bacteria deep within solid meat products. The choice between direct and vapor application depends on the type of meat product, target microbes, and packaging conditions.

In recent years, encapsulation techniques have become innovative methods for delivering essential oils (EOs) in meat systems, merging direct and controlled-release applications. Encapsulation protects EO molecules by entrapping them in carriers like emulsions, liposomes, or biopolymer matrices, which control their release. For instance, nanoemulsions, which are oil-in-water emulsions with droplet sizes in the nanometer range, can be mixed into meat batters or sprayed onto surfaces [41]. These tiny droplets, stabilized by food-grade emulsifiers, enhance EO distribution and reduce rapid evaporation, improving contact with microorganisms while minimizing strong aroma intensity [41].

Liposomes, another encapsulation strategy, consist of phospholipid bilayer vesicles that can carry hydrophobic EO components in their lipid phase, allowing for better stability and a more controlled antimicrobial effect [42]. Encapsulation addresses challenges like volatility and poor water solubility of EOs, enabling reduced effective doses and gradual release during storage, which extends shelf life [43]. Encapsulation has shown promising results in preserving meat quality. For example, thyme essential oil in nanoliposomes demonstrated a strong bacteriostatic effect against *Salmonella enteritidis* in chicken meat without negatively impacting sensory qualities [42] Similarly, *Zataria multiflora* essential oil in nano-liposomal form exhibited enhanced antioxidant and antimicrobial activity in beef patties compared to free oil [44]. Other systems, such as biopolymer nanoparticles and solid lipid nanoparticles, have also been explored for protecting EOs and modulating their release [45].

Overall, encapsulated EOs allow for controlled release, maintaining inhibitory concentrations longer and reducing initial aroma bursts [45]. This approach aligns with vapor-phase concepts, where EOs can be encapsulated in coatings that release them into the package atmosphere over time. Advances in delivery methods, from vapor-phase systems to nanoencapsulation, enable food scientists to optimize antimicrobial efficacy while preserving meat quality [36]. By selecting or combining application methods, the benefits of EOs can be maximized to enhance meat product safety and shelf life.

Antimicrobial mechanisms of essential oils

Cell membrane disruption

Essential oils interact with the lipids in the cell membranes of microorganisms due to their hydrophobic nature. This interaction disrupts the cell membrane, leading to leakage of cytoplasmic contents and cell death [46,47]. Furthermore, the hydrophobic components of EOs can penetrate the lipid bilayer, causing structural and functional damage to the membrane [46,48].

Reactive oxygen species (ROS) generation

EOs can induce the production of ROS within microbial cells. The oxidative stress caused by ROS can damage cellular components, including proteins, lipids, and DNA, leading to cell death [47].

Enzymatic inhibition and DNA damage

EOs can inhibit essential enzymes and cause DNA degradation, further contributing to their antimicrobial effects [47].

Antioxidant mechanisms of essential oils

Free radical scavenging

Essential oils are composed of compounds that have the ability to neutralize free radicals, thereby preventing oxidative injury to food products. This process serves in delaying lipid oxidation and improving food quality [49–51]. The free radical is neutralized through the acceptance of a hydrogen atom from the antioxidant compound, leading to the creation of a more stable molecule that is defined by a low standard reduction potential [52]. The resonance delocalization in the ring structure of phenolic substance determines the stability of antioxidant radicals [53]. Examples of compounds that possess the ability to neutralize free radicals include carotenoids, ascorbic acid, flavonoids, lignans, butylated hydroxytoluene (BHT), and butylated hydroxyanisole (BHA) [54]. Nonetheless, the effectiveness of antioxidants is influenced by various factors, including the delocalization of antioxidant radicals, pH levels, and reduction potential. The transfer of hydrogen from the antioxidant to the free radicals in food exhibits thermodynamic stability when the bond dissociation energy in the antioxidant is low [55]. The capacity of antioxidants to donate hydrogen increases as their reduction potential decreases [53].

Metal chelating

The activation energy in the initiation stage is lowered when metal is present during oxidation. In particular, metal catalyzes the production of hydroxyl radicals by hydrogen peroxide and removes the hydrogen from food radicals [56]. Metal chelating prevents oxidation by preventing the development of insoluble metal complexes, metal redox cycling, and steric barrier between metals and dietary ingredients [57]. Ascorbic acid, polyphenols, lignans, and amino acids are among the antioxidant substances that have been identified as metal chelators [58].

Singlet oxygen quenching

The quenching process may involve both physical and chemical mechanisms. Singlet oxygen undergoes deactivation and conversion into ground-state triplet oxygen via physical quenching, facilitating the transfer of charge or energy [59]. A single-state charge transfer complex is created when the quencher donates an electron to the singlet oxygen. The complicated transitions to the triplet state occur via the intersystem crossing mechanism. Ultimately, a quencher and triplet oxygen are linked to the triplet state charge transfer complex. However, the chemical quenching method produces oxidation products through a quencher oxidation reaction [60].

Mechanisms of meat deterioration

Microbial spoilage

Growth of spoilage and pathogenic microorganisms

Fresh meat is highly susceptible to microbial growth due to its nutrient-rich and high-water content. While internal tissues of living animals are sterile, contamination occurs during slaughter and processing [61]. Bacteria from equipment, handlers, and the environment colonize the meat surface, leading to spoilage, which is primarily driven by microbial contamination rather than autolytic enzyme activity or chemical oxidation [62]. Pathogenic bacteria, such as *Salmonella* and *Escherichia coli*, may not show obvious spoilage signs but pose food safety risks, while spoilage microorganisms like *Pseudomonas* spp. actively deteriorate meat quality without necessarily causing illness.

The growth of spoilage and pathogenic microbes in meat is influenced by intrinsic factors such as pH, water activity (a_w), and nutrient composition. Post-mortem meat pH typically ranges from 5.5 to 5.8, allowing many spoilage bacteria to thrive despite their preference for near-neutral pH. The high water activity of fresh meat (approximately 0.99) supports microbial proliferation, as most bacteria require $a_w > 0.90$ [63]. Extrinsic factors, including temperature, humidity, and oxygen availability, also significantly affect microbial growth rates. For example, improper storage temperatures above 5 °C can accelerate bacterial growth, leading to spoilage within days [61]. In contrast, strict cold storage (0–4 °C) can extend shelf-life by delaying bacterial growth. Additionally, humidity and packaging conditions influence microbial survival, with high humidity favoring bacteria and oxygen-rich environments promoting aerobic spoilage. In conclusion, meat spoilage and pathogen growth are determined by initial contamination and growth conditions, emphasizing the need to control factors like temperature, pH, and moisture to suppress microbial proliferation [61,63].

Common spoilage bacteria and their impact on meat quality

Microorganisms can spoil meat, with specific bacterial groups being primarily responsible for quality defects. Studies indicate that in chilled fresh meats stored aerobically, *Pseudomonas* and *Brochothrix* are often the main spoilers [61]. *Enterobacteriaceae* also frequently appear, particularly in processed or temperature-abused meats. Each group affects meat quality through changes in odor, texture, and appearance.

— *Pseudomonas* spp.: This Gram-negative, aerobic genus thrives at refrigeration temperatures and is a leading cause of spoilage in raw meat stored in air. They metabolize meat nutrients, producing volatile compounds that create off-odors described as "fruity" or "putrid" [64]. High populations lead to dense colonies and a slimy film on the meat, resulting in a wet and soft texture. Certain strains can discolor meat, such as *P. fluorescens*, which may create a greenish sheen [61]. Overall, *Pseudomonas* spoilage is marked by sticky surfaces, strong off-odors, and loss of color.

— *Brochothrix thermosphacta*: This Gram-positive, non-sporeforming rod is a major spoilage organism in both aerobic and anaerobic conditions [65]. It ferments sugars and amino acids, producing off-odors like "buttery" or "sour dairy" [65]. While it does not produce heavy slime, it can contribute to surface tackiness and discoloration [61]. *B. thermosphacta* is tolerant of low-oxygen conditions and often indicates advanced spoilage, particularly when accompanied by characteristic odors.

— *Enterobacteriaceae*: This family includes facultative anaerobic Gram-negative rods that can spoil meat, often contaminating it during slaughter or processing. They are typically outcompeted by pseudomonads in fresh meat but become significant in minced or vacuum-packaged products. Their spoilage is evident through strong decompositional odors and discoloration. Some members produce colored pigments or slime, contributing to surface stickiness [61]. Their presence is associated with unacceptable smells and compromised meat quality, and some strains pose food safety risks due to their pathogenic nature.

Role of moisture and storage conditions in microbial contamination

— **Moisture availability (water activity):** Moisture is a critical factor in microbial spoilage, as bacteria require water to grow, and the high water content of meat renders it inherently perishable. Water activity (a_w) measures the availability of free water for microbial use;

fresh beef, with an a_w close to 0.99, offers near-optimal conditions for bacterial proliferation [63]. Consequently, when other environmental conditions are favorable, bacteria can multiply rapidly on meat surfaces. Controlling a_w has long been a fundamental preservation strategy, involving methods such as drying, salting, or the addition of curing salts to bind water. Lowering a_w effectively inhibits microbial growth [61], emphasizing the importance of moisture control. High-moisture meat or storage under high-humidity conditions accelerates microbial activity, whereas reducing available moisture can significantly prolong shelf-life. For example, meats stored in environments with reduced relative humidity may develop a dry surface "crust" that resists bacterial colonization although this may alter the product's appearance. This highlights the central role of a_w in limiting microbial spoilage. In summary, meat products with higher levels of free moisture are substantially more susceptible to microbial contamination and deterioration than drier counterparts.

— **Storage conditions and cross-contamination:** Proper storage conditions are essential to prevent microbial spoilage of meat. Among these, temperature is the most critical factor: maintaining meat at refrigerated or frozen temperatures significantly slows bacterial growth, whereas improper storage commonly referred to as temperature abuse can accelerate spoilage. Even psychrotrophic spoilage bacteria exhibit markedly faster growth at moderately elevated temperatures (8–10 °C compared to 0–4 °C), leading to a substantial reduction in shelf-life by several days [61]. When meat is left at ambient temperature, mesophilic bacteria including pathogenic microorganisms can proliferate rapidly, reaching hazardous levels within hours and posing both spoilage and food safety risks. The storage atmosphere also plays a key role: aerobic conditions promote the growth of organisms such as *Pseudomonas* (as previously discussed), whereas vacuum or modified-atmosphere packaging can inhibit aerobic microbes but may permit the growth of anaerobes or lactic acid bacteria. Therefore, selecting appropriate packaging and gas composition is crucial for targeting specific spoilage organisms. For instance, high-CO_2 modified atmospheres are effective in suppressing *Pseudomonas* growth and can thereby extend the shelf-life of meat [62]. However, elevated carbon dioxide or reduced oxygen levels do not eliminate spoilage; instead, they shift the dominant microbial population toward species that tolerate such environments (e. g., *Brochothrix* or lactic acid bacteria), which typically cause different spoilage manifestations, such as souring rather than putrid odors.

Storage of meat is crucial to prevent cross-contamination, which can lead to spoilage or pathogenic microbes from external sources. Human handling and equipment in processing plants are major vectors of contamination, with unclean gloves, coughing, and movement between areas being major causes. Inadequate sanitation can lead to bacteria from one carcass or surface transferring to others. The processing environment often harbors resilient microbes, such as *Brochothrix thermosphacta*, which can form biofilms on surfaces, protecting bacteria and allowing them to persist [65]. Interventions like refrigeration, humidity control, sanitation, and natural preservatives are vital for maintaining meat product quality [63,61]. By managing water activity, storage conditions, and preventing contamination, the shelf-life of meat can be significantly extended, and microbial spoilage can be slowed.

Oxidation in meat product

Meat and meat products are susceptible to bacterial and chemical degradation due to their high nutritional content. The primary factor contributing to nonmicrobial deterioration in meat and meat products is oxidation. Generally, the process of oxidation leads to the removal of electrons when meat interacts with oxygen [66]. The occurrence of lipids and proteins in meat renders them susceptible to oxidation, especially since natural antioxidants diminish rapidly after slaughter [67]. Moreover, the degree of its susceptibility is affected by the types of muscle, breeds of animals, and spices [68]. The methods utilized for processing and preservation significantly impact the degree of oxidation, encompassing elements like irradiation, cooking, freezing, chilling, additives, and packaging [66].

Lipid oxidation

Lipid oxidation occurs in the muscles, starting at the stage of slaughter and persisting through the processing of animals, influenced by environmental factors and the limited antioxidant capacity of meat [69]. Lipid oxidation is acknowledged for leading to undesirable flavors, changes in color, shortened shelf life, unpleasant odors, and potential toxicity in meat products [70]. Despite these negative outcomes, lipid oxidation is considered preventable and strongly affects the nutritional integrity of meat and derived products [71]. Moreover, it contributes to the progressive decline of sensory qualities, which are crucial for consumer acceptance [72]. Among food constituents, lipids are one of the least stable components and are highly prone to oxidative degradation [68]. Oxidation in lipids may proceed through three principal pathways: photooxidation, enzymatic oxidation, and autoxidation [73]. The mechanism involves unsaturated fatty acids reacting with oxygen in a free radical chain reaction, producing hydroperoxides as the primary oxidative products [74]. Unlike other lipid oxidation products, hydroperoxide does not play a role in the development of odor and aroma. Nonetheless, this compound leads to the formation of a secondary compound due to its high instability, resulting in the production of esters, aldehydes, hydrocarbons, alcohols, and acids [75]. The extent of lipid oxidative stability is affected by several factors, including heat and light exposure, oxygen availability, the balance of antioxidants and prooxidants, and the degree of unsaturation of fatty acids [71].

Furthermore, the constituents found in muscle tissue can function as catalysts, including myoglobin, iron, ascorbic acid, and hydrogen peroxide.

Photo-oxidation

Photo-oxidation occurs especially as a result of ultraviolet (UV) radiation and in the presence of sensitizers, leads to a radical reaction that results in the formation of hydroperoxides. This process differs when it occurs without sensitizers and light [76]. This mechanism differs from the initiation that took place in autoxidation. Hydroperoxides are generated through an alternative pathway rather than the free radical mechanism outlined in autoxidation [77]. The procedure of photo-oxidation involves multiple essential phases. At the outset, light energy is captured, resulting in the excitation of the singlet sensitizer. Following this, the resulting reactions can be classified into three separate pathways:

— The production of singlet oxygen resulting from the interaction between an excited triplet sensitizer and molecular oxygen [78]. Following this, singlet oxygen reacts with the double bonds found in unsaturated fatty acids, resulting in the production of hydroperoxide when alkyl radicals are not present [52].

— The generation of superoxide radical anion occurs when an excited sensitizer reacts with triplet oxygen via electron transfer, leading to the abstraction of hydrogen from unsaturated fatty acids, which subsequently initiates lipid oxidation. Furthermore, the interaction between superoxide radical anion and hydrogen peroxide resulted in the generation of hydroxyl radical and singlet oxygen. The products have the potential to induce lipid oxidation through interactions with fatty acids. The metal can facilitate this process [53].

— The abstraction of hydrogen can lead to the formation of alkyl radicals in unsaturated fatty acids through the action of an excited triplet sensitizer [52]. The subsequent reaction involves an alkyl radical that interacts with oxygen, resulting in the formation of a peroxy radical. This process can trigger lipid oxidation by abstracting hydrogen from neighboring fatty acids [78].

Enzymatic oxidation

Lipoxygenase performs a crucial role in enzymatic oxidation, enabling the transfer of oxygen to the hydrocarbon chain of fatty acids. The reaction produces hydroperoxides and peroxides that feature conjugated double bonds [76]. The concentration of lipoxygenase influences the rate of lipid oxidation; increased levels of the enzyme accelerate oxidative reactions. The extraction of hydrogen from the methylene group of polyunsaturated fatty acids occurs during the enzymatic oxidation process, resulting in the formation of a conjugated diene system that subsequently interacts with molecular oxygen. The chemical reaction of a peroxy radical with hydrogen linked to another unsaturated fatty acid yields an alkyl radical and a conjugated hydroperoxy diene [79].

Autoxidation

Catalytic agents such as free radicals, temperature variations, pH conditions, and the presence of metal ions play a crucial role in influencing radical-driven reactions in food systems [79]. There are three primary stages of lipid oxidation: initiation, propagation, and termination [66]. The primary mechanism for lipid oxidation in meat and meat products is autoxidation, which occurs when oxygen interacts with unsaturated fatty acids [79]. During the initiation stage, reactive oxygen species (ROS) such as hydrogen peroxide, hydroxyl radicals, and superoxide anions are produced, leading to the activation of oxygen molecules. This activation is often enhanced by catalytic substances in combination with external factors like heat or light exposure. In the propagation step, oxygen reacts with alkyl fatty acids to produce peroxyl radicals (ROO*). These radicals subsequently interact with unsaturated fatty acids to generate lipid hydroperoxides (ROOH). Due to their unstable nature, hydroperoxides degrade into volatile compounds, which are associated with undesirable off-flavors [80], as well as alterations in color, protein function, and overall stability [81]. The alkyl radical will combine with oxygen during the propagation step to create radicals like peroxyl radicals. After that, the previously generated radical might stabilize and take hydrogen from another weak molecule to create a lipid hydroperoxide. Before termination occurs (two R* merge and terminate), the propagation process may take place numerous times [82].

Protein oxidation

The oxidation of protein presents a considerable issue in meat, as it directly affects the quality of a product. Nonetheless, the complex mechanisms governing protein oxidation have not been well investigated. Oxidative modifications in proteins occur along the amino acid sequence [83]. The range of reactive oxygen species (ROS) responsible for protein oxidation includes both radical forms such as superoxide (O_2*), hydroxyl (OH), thiyl (RS), and peroxyl radicals (ROO*), as well as non-radical compounds, such as hydrogen peroxide (H_2O_2) and lipid hydroperoxides (ROOH), along with reactive aldehydes [84]. Several ROS, including superoxide anions, hydroxyl and peroxyl radicals, peroxynitrite, and hydrogen peroxide are capable of initiating oxidative damage to proteins [67]. These reactive species can be generated through multiple pathways, such as exposure to ionizing radiation, redox reactions mediated by enzymes, or metal-catalyzed reactions [85]. Protein oxidation leads to alterations in protein conformation, particularly affecting its secondary and tertiary structures. This occurs when oxidizing agents interact with the protein backbone [67]. The modification of protein is acknowledged as a crucial element affecting its properties, including solubility and gelation, which subsequently impacts the physical quality of meat, such as cooking loss and hardness [86].

At the molecular level, protein oxidation typically begins at the carbon atom of amino acid residues, producing relatively stable protein-centered radicals that subsequently react with molecular oxygen to form alkyl peroxyl radicals. These peroxyl radicals may either degrade into imines, which upon hydrolysis cause cleavage of the protein backbone, or interact with nearby molecules to produce hydroperoxides [85]. Protein oxidation begins with hydrogen abstraction, resulting in the generation of protein radicals that subsequently interact with molecular oxygen [67]. Oxidation induces modifications to proteins encompassing cross-linking and fragmentation of the protein [85].

Factors affecting lipid oxidation in meat products

The process of lipid oxidation in meat encompasses intricate reactions involving both substrates and catalysts, along with various mechanisms at play. The elements influencing lipid oxidation include the composition of meat, which is an intrinsic factor, as well as the methods of processing and storage, which are considered extrinsic factors [87]. The progression and stability of lipid oxidation are strongly influenced by the balance between pro-oxidant and antioxidant agents present in the system [87]. Among the intrinsic components of meat, fatty acids represent the most critical factor determining oxidative susceptibility. However, other catalytic contributors such as transition metals, heme proteins, intrinsic antioxidant compounds, and pro-oxidant enzymes also play an important role in driving these reactions. In addition, extrinsic factors related to the animal itself, including genetic background, feeding regimen, production system, and even the specific muscle type, can alter meat composition and, consequently, modulate its oxidative behavior [68]. Furthermore, the existence of light or oxygen significantly affects the process of oxidation. The storage conditions significantly influence the rate of oxidation [77]. Essentially, every stage in the processing of muscle can facilitate oxidation, including cutting, deboning, and cooking [88].

Fatty acids

The quantity of fat and the composition of fatty acids are critical elements in the progression of lipid oxidation [89]. The level of fat unsaturation exhibits an exponential correlation with oxidation stability [74]. The presence of additional double bonds increases the susceptibility of meat to oxidation reactions [90], with (E)-isomers exhibiting greater vulnerability compared to trans isomers. Furthermore, an increase in the chain length of fatty acids will lead to a rise in oxidation [91].

Metals and heme protein

The catalytic role of metals, whether present in free form or bound within heme proteins, is a major factor driving oxidative reactions in meat [78]. Within muscle tissue, iron primarily occurs in myoglobin and hemoglobin, as well as within the active centers of specific enzymes. Among these, myoglobin and hemoglobin are the most abundant heme proteins in meat, and their degradation can release iron into the system [78]. The amount of heme protein varies depending on both the muscle type and animal species, and this concentration is a key determinant of oxidative stability. Heme proteins function as catalysts that accelerate the generation of reactive oxygen species. Their interaction with lipids is mutually reinforcing, as lipid peroxidation can enhance heme protein oxidation and vice versa [70]. Moreover, acidic conditions further promote the susceptibility of heme proteins to oxidation [78]. During lipid oxidation, aldehydes are produced, which destabilize the redox state of heme proteins and stimulate oxidation processes mediated by oxy-heme proteins [70].

Prooxidant enzymes

Meat contains various enzymes that have the potential to facilitate oxidation processes. The presence of polyunsaturated lipids leads to the production of active catalysts by those enzymes [77]. Lipoxygenase serves as the primary enzyme responsible for lipid oxidation, functioning by abstracting hydrogen from the allylic methylene position of polyunsaturated fatty acids [92]. This enzyme is involved in the initial phase of the process. Myeloperoxidase is another enzyme that facilitates lipid oxidation in meat tissue. This enzyme is present when meat comes into contact with blood during the slaughter process. The interaction between H_2O_2 and chloride results in the formation of hypochlorous acid, which subsequently reacts with $O_2{\bullet}^-$, leading to an increase in •OH levels.

Endogenous antioxidants

Various antioxidant substances present in meat influence the speed of lipid oxidation. The compounds serve to shield meat from the influence of free radicals or catalysts that promote oxidation. The primary categories of antioxidants are classified into three main groups: vitamins, peptides, and enzymes. The capacity of these compounds to neutralize radicals is critically evaluated in the oxidation process [53]. Vitamin E is the primary vitamin found in animal tissue. The protective mechanism involves a significantly higher rate of lipid radical attack on α-tocopherol compared to lipids. Consequently, it safeguards unsaturated fatty acids from the assault of free radicals. In the oxidation process, α-tocopherol transfers a hydrogen atom lipid peroxy radical, effectively scavenging the peroxy radicals and resulting in the formation of a tocoperoxy radical [53].

Peptides

Peptides play a role in oxidative stability through mechanisms such as radical scavenging, metal chelation, and the reduction of hydroperoxides. The antioxidant activity of the peptide is significantly influenced by the amino acids present in its chemical structure [87]. A variety of peptides exhibiting antioxidant properties include leucine, valine, tyrosine, histidine, methionine, and tryptophan within their amino acid sequences. The peptide containing tyrosine or tryptophan functions in the oxidation process by scavenging free radicals, whereas histidine operates by chelating metals like copper or iron [93]. Moreover, the predominant dipeptides include carnosine and anserine, which function by scavenging free radicals and chelating metals [93].

Enzymes

The main enzymes that play a role in preventing oxidation are catalase, glutathione peroxidase, and superoxide dismutase [92]. They impede oxidation via multiple mechanisms. For example, the role of superoxide dismutase includes the removal of $O_2{\bullet}^-$ and the generation of oxygen and H_2O_2 [93].

Storage condition

The primary factor affecting lipid oxidation is the storage condition, which includes both time and temperature. The oxidation process is enhanced by both time and temperature, with an increase in oxidation observed as the temperature rises [53]. Variations in temperature encourage oxidation by facilitating the formation of ice crystals, which in turn leads to the release of prooxidants and promotes oxidation due to cellular damage [94]. Moreover, meat subjected to freezing and thawing periods is susceptible to oxidation [92]. Furthermore, extended storage durations facilitate the release of iron from heme-protein, leading to reactions during both the initiation and propagation phases [92].

Effects of essential oils in meat products

In recent years, essential oils (EOs) have gained increasing attention as natural preservatives in meat and meat products due to their antimicrobial and antioxidant properties. This section presents a comparative review of selected research articles that evaluate the application of essential oils and their nano-based delivery systems on different types of meat, including beef, pork, camel, and ostrich. The studies highlight their effects on physicochemical parameters such as lipid oxidation (e. g., TBARS and peroxide values), microbial spoilage, sensory quality, and shelf-life extension.

Table 1 summarizes various essential oils (EOs) that have been evaluated for their application in meat products, highlighting their active compounds, the type of meat tested, and their mechanisms of action. For instance, thymol and carvacrol, the key components of basil and thyme essential oils, were effective in preventing fat oxidation in minced pork by scavenging free radicals responsible for rancidity [96]. Similarly, combination of rosemary, thyme, and clove EOs could retard lipid oxidation and inhibit microbial growth in mechanically deboned chicken meat proteins due to the ability of phenolic compounds to disrupt bacterial membranes [96]. On the other hand, Shahbazi et al. investigated the effects of thyme and cinnamon EOs on ground beef and showed that compounds, such as cinnamaldehyde, benzaldehyde, limonene, linalool, and eugenol not only inhibited microbial growth but also enhanced sensory properties such as aroma and flavor [98].

Several essential oils (EOs) have been extensively studied for their preservative effects in meat products, particularly due to their antimicrobial and antioxidant properties. For instance, blue mint bush EO, which contains carvacrol, thymol, and p-cymene, demonstrated strong antimicrobial activity in chicken meatballs by disrupting microbial cell walls, thus prolonging shelf life [98]. Similarly, rosemary EO, rich in carnosol, carnosic acid, and rosmanol, inhibited microbial growth and lipid oxidation in chicken meatballs, improving both safety and sensory quality [99]. In cooked pork sausages, nutmeg EO showed potential to slow down lipid oxidation and inhibit microbial growth due to the action of its compounds such as borneol, geraniol, and linalool, while also enhancing aroma [101].

Clove EO, with eugenol as the main compound, exhibited dual antioxidant and antimicrobial effects in Chinese bacon. It scavenged free radicals and reduced lipid oxidation markers such as malondialdehyde (MDA) and peroxide value (POV). Microencapsulation using β-CD-MOFs further improved its stability and efficacy [103]. Likewise, cinnamon EO (cinnamaldehyde) disrupted microbial membranes and extended the microbial shelf life in various meat types, including pork and chicken [104]. In beef *Mentha pulegium* EO inhibited a broad spectrum of microbes and lowered TBARS and TVB-N values, indicators of oxidative spoilage. Its nanoencapsulated form (16 ppm) significantly enhanced bioavailability and stability [105]. Meanwhile, Litsea EO, composed of citral and d-limonene, showed strong antibacterial activity in duck meat by damaging bacterial cell walls. Its nanoemulsion form also improved solubility and stability, resulting in a more effective preservation effect [106]

Essential oils derived from ajwain (Carum copticum) and cardamom, formulated into nanoemulsions, have demonstrated significant antimicrobial and antioxidant activities in processed meat products such as Mortadella sausage during cold storage. These nanoemulsions improved the sensory quality and texture of the product while extending its shelf life by inhibiting the growth of *Staphylococcus aureus* and enhancing protein stability and moisture retention [112]. Additionally, the use of *Thymus fedtschenkoi Ronniger* essential oil combined with thymoquinone in a starch-based coating exhibited high efficacy in suppressing the growth of *Listeria monocytogenes* and *Salmonella enteritidis* on chicken fillets over 12 days of storage. Active compounds such as thymol and carvacrol act by disrupting bacterial cell membranes, increasing permeability, and inhibiting vital enzyme activities, thereby reducing microbial viability [109]. These findings highlight the potential of essential oils, particularly when

Table 1. The effect of essential oils in meat products

Type of EO	Key compounds	Type of meat	Mechanism of action	Reference
Basil or thyme EO	Thymol, carvacrol	Minced pork meat	Prevents fat oxidation	[95]
Rosemary, thyme, clove	Cymol, α-pinene, eucalyptol	Mechanically deboned chicken meat protein	Retard oxidation and inhibit microbial activity	[96]
Thyme and cinnamon	cinnamaldehyde, benzaldehyde, limonene, linalool and eugenol	Ground beef	Inhibit microbial growth and improve sensory qualities	[97]
Blue mint bush	Carvacrol, thymol, p-cymene	Chicken meatball	Inhibits microbial growth	[98]
Rosemary	Carnosol, carnosic acid, rosmanol, rosmadiol	Chicken meatball	Inhibits microbial growth, reduces lipid oxidation, improves sensory quality	[99]
Thyme	Thymol	Dried meat (jerky)	Inhibits microbial growth	[100]
Nutmeg	Borneol, geraniol, linalool	Cooked pork sausage	Slows lipid oxidation, inhibits microbial growth, improves aroma quality	[101]
Oregano	Carvacrol and thymol	Dried meat (jerky)	Inhibits microbial growth, improves sensory properties	[102]
Thyme	Thymol, Carvacrol, p-cymene, γ-terpinene	Pork, turkey, broiler, beef, and processed meats (e. g. salami)	Disruption of cell membranes, leakage of intracellular contents, inhibition of respiration and energy metabolism	[37]
Clove	Eugenol	Chinese bacon (preserved meat product)	Scavenges free radicals, reduces lipid oxidation	[103]
Cinnamon	Cinnamaldehyde	Pork filet, pork bacon, chicken filets, chicken skin, salmon, scampi	Inhibits microbial growth by disrupting microbial cell membranes	[104]
Oregano	Carvacrol, Thymol	Pork filet, salmon	Disrupts bacterial cell walls and cytoplasmic membranes	[104]
Thyme	Carvacrol, Thymol	Pork filet, scampi	Affects membrane permeability, interferes with microbial enzyme systems; extends microbial shelf life	[104]
Pennyroyal	Pulegone, Menthone, Isomenthone (typical for *M. pulegium*)	Beef meat	Inhibits growth of aerobic mesophilic bacteria, lactic acid bacteria, *Pseudomonas*, molds, and yeasts.	[105]
Litsea	Citral, d-limonene	Duck meat	Destroys bacterial cell wall (notably against *Staphylococcus aureus*), enhances water solubility, reduces volatility, and improves stability, enhances preservation effect	[106]
Myrtle	1,8-Cineole, Myrtenyl acetate, α-Pinene, Linalool	Ostrich meat	Reduces lipid oxidation, protein oxidation, stabilizes pH, and preserves phenolic content. Improves flavor and acceptability, and enhances stability and efficacy.	[107]
Artemisia afra	carotenes, xanthophylls, flavonoids)	Broiler chicken	Improves slaughter weight, meat pH, water-holding capacity, and intramuscular fat. Enhances fatty acid profile. Stabilizes oxidation post-mortem.	[108]
Calamansi	D-limonene (52.64 %), α-pinene (17.29 %)	Chicken breast	Cell wall damage, cell membrane disruption, intracellular content leakage, inhibition of virulence genes, inhibition of biofilm formation and metabolic activity, is effective in preservation, and maintains sensory quality during cold storage	[109]
Pimenta	Eugenol, methyleugenol, β-caryophyllene	Turkey (breast meat and skin)	Disrupts cell membranes, reducing viability; exhibits antimicrobial synergy with peracetic acid (PAA), reducing spoilage organisms such as *Pseudomonas*, lactic acid bacteria, total aerobic bacteria, and psychrophilic bacteria	[110]
Ajwain	Thymol (~50 %)	Mortadella sausage	Disrupts bacterial cell membranes, enhances shelf-life and color, reduces fat and improves protein level	[111]
Cardamom	1,8-cineole, α-terpinyl acetate, linalool	Mortadella sausage	Antioxidant and antimicrobial properties, enhances sensory profile (taste, aroma), nanoemulsion increases bioavailability and product acceptability	[111]
Thymus fedtschenkoi Ronniger	Thymol, Carvacrol, Thymoquinone	Chicken fillets	Disrupts bacterial cell membranes, increases permeability, inhibits enzyme activity, and reduces cell viability	[112]

integrated with nanotechnology and biopolymer-based systems, as natural and innovative solutions to enhance the microbial safety and sensory quality of meat products during storage.

Conclusion

Essential oils are effective natural preservatives for meat products due to their antimicrobial and antioxidant properties. Their efficacy is influenced by concentration, food composition, and application method. Encapsulation techniques improve EO stability and reduce sensory impact. With proper formulation, EOs offer a clean-label solution to extend shelf life and enhance meat product safety, aligning with current consumer demands.

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