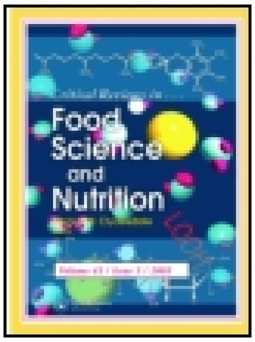

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REVIEW

Essential oils as natural antimicrobials applied in meat and meat products—a review

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ABSTRACT
Meat and meat products are highly susceptible to the growth of micro-organism and foodborne pathogens that leads to severe economic loss and health hazards. High consumption and a considerable waste of meat and meat products result in the demand for safe and efficient preservation methods. Instead of synthetic additives, the use of natural preservative materials represents an interest. Essential oils (EOs), as the all-natural and green-label trend attributing to remarkable biological potency, have been adopted for controlling the safety and quality of meat products. Some EOs, such as thyme, cinnamon, rosemary, and garlic, showed a strong antimicrobial activity individually and in combination. To eliminate or reduce the organoleptic defects of EOs in practical application, EOs encapsulation in wall materials can improve the stability and antimicrobial ability of EOs in meat products. In this review, meat deteriorations, antimicrobial capacity (components, effectiveness, and interactions), and mechanisms of EOs are reviewed, as well as the demonstration of using encapsulation for masking intense aroma and conducting control release is presented. The use of EOs individually or in combination and encapsulated applications of EOs in meat and meat products are also discussed.

KEYWORDS
Essential oils; antimicrobial activity; foodborne pathogens; encapsulation; natural preservatives; meat products

1. Introduction

Meat consumption is rapidly increasing due to the growing world population and world economy (Lee et al. 2020; Ponnampalam et al. 2019). Meat and meat products contain various nutrient compositions, including high-quality protein content, essential amino acids, B-group vitamins, minerals, and other nutrients (Pateiro et al. 2021), ideal for the growth and propagation of meat spoilage micro-organisms and common foodborne pathogens (Zhou, Xu, and Liu 2010). Atmospheric oxygen, temperature, moisture, light, endogenous enzyme activity, and growth of micro-organisms determine the quality and shelf life of meat (Chivandi et al. 2016), of which the growth of micro-organisms is regarded so far the most significant factor in maintaining the safety and quality of meat although deteriorations can occur without micro-organisms (Zhou, Xu, and Liu 2010). The major principle of meat quality control is to eliminate or reduce microbial deterioration (Niyonzima et al. 2015) following Food safety objectives (FSO) and hazard analysis & critical control point (HACCP) systems (Liu et al. 2021).

The spoilage of meat and meat products is associated with bacteria such as *Salmonella* spp., *Campylobacter jejuni*, *Escherichia coli* O157:H7, *Listeria monocytogenes*, *Clostridium* spp, *Pseudomonas*, *Acinetobacter*, *Brochothrix thermosphacta*, *Lactobacillus* spp., *Enterobacter*, etc., as well as molds and yeasts, which can cause outbreaks which severely affect public health and the economy (Li et al. 2020; Jayasena and Jo 2013). Current preservation methods include heating, chilling, high pressure, packaging, ionizing radiation, chemical preservative, bioactive compounds, and hurdle technologies (combining current and new food preservation techniques) (Jayasena and Jo 2013; Kalogianni et al. 2020).

The high use of synthetic additives in food has raised many carcinogenic and toxic problems (Jayasena and Jo 2013; El-Wahab and Moram 2013). Colorants and flavor were found to cause cancer and lead to DNA damage (Kumar et al. 2019). In addition, well-known food additives such as benzoates can initiate allergies such as erythrasma and asthma and are believed to result in brain damage (Pandey and Upadhyay 2012). Due to the growing concerns regarding the food safety and harm of chemical and synthetic preservatives, natural antimicrobials have been the attractive alternative trend for the food market (Falleh et al. 2020). Plant extracts, essential oils, peptides, vitamin C (ascorbic acid), vitamin E (tocopherols), and protein hydrolysates have been proposed to prevent oxidation in processed meat products (Carocho et al. 2014; Jiang and Xiong 2016).

Essential oils (EOs), a rich mixture of diverse bioactive chemical components, are aromatic and volatile liquids extracted from plant materials, such as flowers, roots, bark, regarded as secondary metabolites (Hyldgaard, Mygind, and Meyer 2012; Hassoun and Emir Çoban 2017). EOs are

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widely accepted by consumers, attributing their high volatility, ephemeral, and biodegradable nature (Falleh et al. 2020). Some EOs are generally recognized as safe (GRAS) by the Food and Drug Administration (FDA) (Kalogianni et al. 2020). EOs and their components have shown excellent antibacterial, antiparasitic, insecticidal, antiviral, antifungal, and antioxidant properties in previous research (Hyldgaard, Mygind, and Meyer 2012). Considering the application in meat and meat products, EOs from oregano, rosemary, thyme, clove, cinnamon, mustard, and garlic have shown a greater potential to be used as an antimicrobial agent (Aziz and Karboune 2018; Chivandi et al. 2016; Ghabraie et al. 2016a).

Generally, higher doses of EOs are required for their application on meat and meat products (Jayasena and Jo 2013). Food pH, storing temperature, contamination levels, and the interactions of hydrophilic compounds of EOs with food matrix components such as fats, carbohydrates, proteins, and salts could affect the antimicrobial activity of EOs (Hyldgaard, Mygind, and Meyer 2012). Encapsulation tends to mask the unwanted smells or flavors of EOs by coating or entrapping EOs within another inert shell material, isolating and protecting the core materials from inactivation by reacting with the food ingredients discussed above (Castro-Rosas et al. 2017; Gómez et al. 2018; Turasan, Sahin, and Sumnu 2015). The proper wall materials should have good mechanical strength that can offer firm protection to core materials, be compatible with food products, adapt to different environmental conditions, and conduct controlled release (de Souza et al. 2018; Majeed et al. 2015). There are several wall materials mostly used for encapsulation of EOs such as chitosan, gelatin, whey protein, gum arabic, maltodextrin, sodium caseinate, and modified starches (Gómez et al. 2018; Majeed et al. 2015). Generally, there are four main encapsulation types including (i) particles: matrix where EOs are dispersed; (ii) capsules: a membrane surrounds the core of EOs; (iii) complexes: EOs are stabilized in cavities by chemical interactions; and (iv) droplets: EOs dispersed in a solvent with surfactants (Maes, Bouquillon, and Fauconnier 2019).

This review provides an overview of the published data on the antimicrobial activity of EOs and their components that could be potentially applied in meat and meat products. The current understanding of the possible mechanisms, synergies, limitations, and encapsulations of EOs was also presented.

2. Microbial deterioration of meats

Meat is a complex food ecological niche and rich in essential nutrients that strongly support the growth of a large number and variety of micro-organisms (Jayasena and Jo 2014; Russo et al. 2006). The presence and growth of spoilage micro-organisms in meat and meat products can differ depending on the storage conditions such as temperature, water activity, and oxygen availability (Hernández-Macedo, Barancelli, and Contreras-Castillo 2011; Labadie 1999). *Pseudomonas* spp. and lactic acid bacteria are always the dominant bacteria when meats are stored aerobically at chilled temperatures and refrigerated temperatures, respectively (Labadie 1999; Berruga, Vergara, and Gallego 2005; Hernández-Macedo, Barancelli, and Contreras-Castillo 2011; Russo et al. 2006). Lactic acid bacteria can produce H_2S from cysteine, causing sour off-flavors, which thereafter oxidize myoglobin to metmyoglobin giving meat green colors (Hernández-Macedo, Barancelli, and Contreras-Castillo 2011). Some LAB, like *Lactobacillus carnosum,* also produces CO_2 attributing to the “blowing” of vacuum packages (Doyle 2007; Hernández-Macedo, Barancelli, and Contreras-Castillo 2011). *Brochothrix thermosphacta* has always been abundant in meats stored in aerobic or anaerobic conditions. It can metabolize glucose into lactic acid in anaerobic conditions, and subsequently, lactic acid into ethanol in aerobic conditions results in off-odors (Chaillou et al. 2015; Pin, García de Fernando, and Ordóñez 2002).

The great concern for causing outbreaks in the EU and USA includes *Salmonella* spp., *Escherichia coli* O157:H7, and other enterohemorrhagic *E. coli* (ETEC), *L. monocytogenes* and bacterial toxins produced by *Bacillus* spp., *Staphylococcus* spp. (*S. aureus*), and *Clostridium* spp. (Jayasena and Jo 2013; Kalogianni et al. 2020). The growth of toxin-producing bacteria in meat is mainly responsible for the foodborne illness on consumption (Kalogianni et al. 2020). *Escherichia coli* O157:H7 was reported in beef (Chaillou et al. 2015; Gutema et al. 2021), fermented and dried meats (Balamurugan et al. 2020; Muthukumarasamy and Holley 2007) that can cause severe symptoms of hemorrhagic colitis and hemolytic uremic syndrome (HUS) (Meng et al. 2012). *L. monocytogenes* proved to be responsible for human listeriosis, which presents commonly in raw poultry, beef, and pork meat (Skowron et al. 2020), ready-to-eat meats (Kurpas et al. 2020), as well as in the meat processing plants which possibly transfered from the plant to meat and meat products during processing because of inefficient hygiene control (Duze, Marimani, and Patel 2021; Buchanan et al. 2017). Fungi like *Penicillium* spp. and *Aspergillus* spp. were determined on dry-cured meats (Álvarez et al. 2020; Freke et al. 2019) or fermented sausages (López-Dı́az et al. 2001; Pleadin et al. 2017), are responsible for the diseases (mycotoxicoses) caused by mycotoxins including majorly aflatoxin B_1(AFB_1) and ochratoxin A (OTA) (Zadravec et al. 2020; Pleadin et al. 2017).

3. Essential oils

3.1. Components of EOs

Essential oils are aromatic oily liquids extracted from parts of plants like flowers, buds, seeds, leaves, fruits, roots, etc. (Burt 2004). The extraction methods, including conventional (steam distillation, hydrodistillation, solvent extraction) and innovative (supercritical fluid extraction, microwave-assisted extraction, ultrasound-assisted extraction) methods, should be appropriately selected for EOs without affecting their characteristics (Pateiro et al. 2018). Essential oils are highly complex mixtures of low molecular weight aromatic compounds (Calo et al. 2015) with diverse antimicrobial

Table 1. Minimum inhibitory concentrations (MIC) of selected common used EOs against food borne pathogens.

Common name	Species	Main components	Pathogens, MIC ppm	References
Mustard	*Sinapis alba*	Allyl isothiocyanate 71%	*Staphyloccocus aureus*, 128 ppm *Micrococcus luteus*, 128 ppm *Staphyloccocus epidermidis*, 256 ppm *Escherichia coli*, 512 ppm *Bacillus subtilis*, 512 ppm *Shigella sonnei*, 512 ppm *Salmonella lignieres*, 256 ppm *Pseudomonas aeruginosa*, 256 ppm *Pseudomonas fluorescens*, 512 ppm	(Peng et al. 2014)
Oregano	*Origanum vulgare*	Carvacrol, thymol	*Aspergillus niger*, 625 ppm *Aspergillus flavus*, 2500 ppm *Aspergillus parasiticus*, 2500 ppm *Penicillium chrysogenum*, 625 ppm	(Hossain et al. 2016)
	Thymus capitatus Hoff.	Cavacrol (81.2), p-Cymene (5)	*L. monocytogenes*, 521 ppm *Staphyloccocus aureus*, 417 ppm *B. cereus*, 261 ppm *S. enterica serovar typhimurium*, 625 ppm *E. coli O157:H7*, 625 ppm *Pseudomonas aeruginosa*, 2083 ppm	(Dussault, Vu, and Lacroix 2014; Casiglia et al. 2019)
	Origanum compactum	Carvacrol (22), γ-terpinene (23), thymol (19)	*E. coli O157:H7*, 250 ppm *Salmonella typhimurium*, 500 ppm *Staphyloccocus aureus*, 130 ppm *L. monocytogenes*, 1000 ppm	(Oussalah et al. 2007)
Cinnamon Chinese cassia	*Cinnamomum cassia*	*Trans*-cinnamaldehyde (87.58), cinnamyl acetate (7.53)	*L. monocytogenes*, 625 ppm *S. aureus*, 625 ppm or 470 ppm or 1042 ppm *B. cereus*, 208 ppm or 261 ppm *S. enterica serovar typhimurium*, 417 ppm or 625 ppm *E. coli O157:H7*, 417 ppm or 470 ppm or 625 ppm *Pseudomonas aeruginosa*, 1250 ppm	(Ghabraie et al. 2016a; Dussault, Vu, and Lacroix 2014)
Cinnamon bark	*Cinnamomum verum*	*Trans*-cinnamaldehyde (40.71–68.52), cinnamyl acetate (2.15–14.25), β-phellandrene (9.02), β-caryophyllene (7.41)	*L. monocytogenes*, 780 ppm or 0.0313% *S. aureus*, 1250 ppm or 2.5 mg/mL *B. subtilis*, 5 mg/mL *E. coli*, 780 ppm or 0.0313% or 10 mg/mL *S. typhimurium*, 1250 ppm or 0.0625% or 10 mg/mL *P. aeruginosa*, 2500 ppm	(Ghabraie et al. 2016a; Kang and Song 2018; Huang et al. 2014)
Red bergamot	*Monarda didyma* L.	Carvacrol (48.21), *p*-cymene (13.98), ɤ-terpinene (12.69)	*L. monocytogenes*, 1250 ppm *S. aureus*, 2500 ppm *E. coli*,1250 ppm *S. typhimurium*, 5000 ppm *P. aeruginosa*, >10,000 ppm	(Ghabraie et al. 2016a)
Lemongrass	*Cymbopogon citratus*	*Citral (63)*	*L. monocytogenes*, 1250 ppm *S. aureus*, 625 ppm *B. cereus*, 156 ppm *S. enterica serovar Typhimurium*, >5000 ppm *E. coli O157:H7*, 5000 ppm *P. aeruginosa*, >5000 ppm	(Dussault, Vu, and Lacroix 2014)
Red Thyme	*Thymus vulgaris*	Thymol, carvacrol, γ-terpinene	*A. niger*, 1250 ppm *A. flavus*, 1250 ppm *A. parasiticus*, 1250 ppm *P. chrysogenum*, 312.5 ppm *L. monocytogenes*, 833 ppm *S. aureus*, 313 ppm *B. cereus*, 417 ppm	(Ghabraie et al. 2016a; Hossain et al. 2016)

(*continued*)

Table 1. Continued.

Common name	Species	Main components	Pathogens, MIC ppm	References
			S. enterica serovar typhimurium, 2083 ppm *E. coli O157:H7,* 1250 ppm *P. aeruginosa,* 3333 ppm	
Winter savory	*Satureja montana* L.	Cavacrol 43.84, γ-Terpinene 12.66, Thymol 6.71	*L. monocytogenes,* 625 ppm *S. aureus,* 625 ppm *B. cereus,* 313 ppm *S. enterica serovar typhimurium,* 1250 ppm *E. coli O157:H7,* 1250 ppm *P. aeruginosa,* >5000 ppm	(Dussault, Vu, and Lacroix 2014; Ben Lagha et al. 2020)
Garlic	*Allium sativum* L.	Diallyl sulfides 42%-53%	*S. aureus,* 24 ppm MRSA, 32 ppm *Candida albicans,* 16 ppm *Candida krusei,* 24 ppm *Candida glabrata,* 32 ppm *Aspergillus niger,* 20 ppm *Aspergillus flavus,* 40 ppm *Aspergillus fumigatus,* 32 ppm	(Tsao and Yin 2001)
Clove	*Eugenia caryophyllus*	Eugenol (83–95), eugenyl acetate (9.96), β-caryophyllene (4.01)	*L. monocytogenes,* 3750 ppm *S. aureus,* 1875 ppm *E. coli,* 1875 ppm *S. typhimurium,* 3750 ppm *P. aeruginosa,* >10,000 ppm	(Ghabraie et al. 2016a)

activities (Jayasena and Jo 2013). The active compounds can be divided into two groups of distinct biosynthetic origin (Bakkali et al. 2008), including the major one of terpenes and terpenoids and the other one of aromatic and aliphatic constituents (phenylpropanoids) (Jayasena and Jo 2013). Terpenes are the combination of isoprenes, a 5-carbon-base (C_5) unit, when contain oxygen terpenes are called terpenoids (Bakkali et al. 2008). The most common terpenes are the monoterpenes (C_{10}) which make up 90% of the EOs, with various structures serving several functions (Bakkali et al. 2008). Aromatic compounds derived from phenylpropane constitute less in EOs. The phenolic compounds with a polar functional group potentially determine the antimicrobial activity of the EOs (Pateiro et al. 2021; Barbosa et al. 2009). Therefore, generally, higher content of phenolic compounds present stronger antimicrobial abilities (Alirezalu et al. 2020).

3.2. Mode of action of EOs

The antimicrobial activity of EOs is not dependent on a single mechanism, and the action is different for the different components of different micro-organisms (Pateiro et al. 2021). Mechanisms have been proposed to be the actions of chemical compounds in EOs (Burt 2004). The most common mechanism of antimicrobial effects is membrane disruption (Pateiro et al. 2021). The accumulation of bioactive compounds in the phospholipid bilayer of the cytoplasmic membrane results in damage of cytoplasmic membranes, increased fluidity and permeability, leakage of intracellular constituents, disruption of embedded proteins, and cell death (Calo et al. 2015; Huang et al. 2014; Pateiro et al. 2021). Greater resistance of Gram-positive bacteria was reported probably due to the thick layer of peptidoglycan of the cell walls (Guimarães et al. 2019). The obstruct of porin channels of the outer membrane of Gram-negative bacteria may have higher resistance to hydrophobic compounds (Bharti et al. 2020). In the previous research, many EOs or their components, such as mustard, thyme, oregano, cinnamon, garlic EOs, and thymol, carvacrol, cinnamaldehyde, eugenol have shown wide-spectrum antimicrobial activities against foodborne pathogens, including *E. coli* (Clemente et al. 2016; Yuan, Teo, and Yuk 2019), *Listeria monocytogenes* (Dussault, Vu, and Lacroix 2014), *Salmonella* Typhimurium (Ghabraie et al. 2016a; Oussalah et al. 2007), and food spoilage fungi such as *Aspergillus* spp. (Clemente, Aznar, and Nerín 2019; Hossain et al. 2016; Kocić-Tanackov and Dimić 2013), *Penicillium* spp. (Clemente, Aznar, and Nerín 2019; Hossain et al. 2016; Li et al. 2014). Mustard EO has 10 times more bactericidal (EOs kill bacterial cells) or bacteriostatic (EOs inhibit the bacterial growth then the microbial cells may recuperate their reproductive ability) effect than cinnamon EO (Clemente et al. 2016; Falleh et al. 2020). This could be explained by the different actions of two EOs. Mustard EO could affect cell membrane, cause leakage of intracellular ATP (Turgis et al. 2009), induce cell cycle arrest and filamentation (Clemente et al. 2016). However, cinnamon EO could act on the membrane producing lumps, increase cell permeability, cause auto aggregation, leakage of electrolytes (Clemente et al. 2016; Huang et al. 2014). It was observed that Chinese cinnamon EO induced less depletion of the intracellular ATP concentration of bacteria than Spanish oregano and savory EOs but reduced more intracellular pH of *E. coli* O157:H7 that affected DNA transcription, protein synthesis, and enzyme activity of bacteria (Oussalah, Caillet, and Lacroix 2006). Garlic EO has great antifungal activities by acting on multiple sites of the hyphae of *P. funiculosum* (Li et al. 2014). EOs act in several ways inhibiting fungal growth, including cell membrane disruption, alteration, inhibition of cell wall formation, dysfunction of the fungal mitochondria, inhibition of efflux pumps, produce reactive oxygen species (Nazzaro et al. 2017).

Table 2. Combination of essential oils or their components and antimicrobial interactions against several micro-organisms by checkerboard method.

EO combination	Micro-organisms	Interaction	Reference
Oregano + thyme	*Paenibacillus amylolyticus, Bacillus cereus*	Synergism	(Ayari et al. 2020)
	A. flavus, A. parasiticus, P. chrysogenum	Synergism	(Hossain et al. 2016)
	E. Cloacae, P. fluorescens,L. innocua	Addition	(Gutierrez, Barry-Ryan, and Bourke 2009)
	L. monocytogenes, S. aureus, Salmonella Enteritidis	Addition	(Reyes-Jurado, Lopez-Malo, and Palou 2016)
	S. Aureus, Salmonella, E. coli, Bacillus cereus	Synergism	(Gavaric et al. 2015)
Cinnamon + mandarin	*A. niger, A. flavus, A. parasiticus, P. chrysogenum,*	No interaction	(Hossain et al. 2016)
Mandarin + oregano	*Paenibacillus amylolyticus, Bacillus cereus*	No interaction	(Ayari et al. 2020)
Eucalyptus + thyme			
Mandarin + tea tree			
Cinnamon + tea tree	*A. niger, A. flavus, A. parasiticus, P. chrysogenum,*	Synergism, Addition	(Hossain et al. 2016)
Peppermint + thyme	*Paenibacillus amylolyticus, Bacillus cereus*		(Ayari et al. 2020)
Oregano + peppermint			
Tea tree + thyme			
Cinnamon + thyme			
Cinnamon + thyme	*L. monocytogenes, E. coli*	Synergism	
	Botrytis cinerea, Penicillium expansum	Synergism	(Nikkhah et al. 2017)
Cumin + cinnamon	*E. coli*		
Thyme + cumin	*L. monocytogenes, Salmonella spp.*		
Cinnamon + parsley	*L. monocytogenes*		
Garlic + bay	*Salmonella spp.*		
Thyme + rosemary	*Salmonella spp.*	Synergism	
	Botrytis cinerea.	Synergism	(Nikkhah et al. 2017)
	Penicillium expansum	No interaction	(Nikkhah et al. 2017)
Cinnamon + rosemary	*Botrytis cinerea, Penicillium expansum*	No interaction	(Nikkhah et al. 2017)
Carvacrol + cinnamaldehyde;	*E. coli, L. innocua*	Synergism	(Requena, Vargas, and Chiralt 2019)
	P. roqueforti	No interaction	(Ju et al. 2020)
	A. niger	Antagonism	(Ju et al. 2020)
Eugenol + carvacrol;	*A. niger*	No interaction	(Ju et al. 2020)
	P. roqueforti,	Synergism	(Ju et al. 2020)
	Escherichia coli O157: H7	Addition	(Yuan, Teo, and Yuk 2019)
Oregano + mustard	*L. monocytogenes, S. aureus, Salmonella enteritidis*	Addition	(Reyes-Jurado, Lopez-Malo, and Palou 2016)
Thyme + mustard			
Eugenol + cinnamaldehyde	*E. coli, L. innocua*	Synergism	(Requena, Vargas, and Chiralt 2019)
Cinnamon + mustard	*A. ochraceus*	Synergism	(Clemente et al. 2016)
	Penicillium verrucosum, Fusarium oxysporum, Penicillium expansum, Aspergillus niger, Botryotinia fuckeliana, Aspergillus flavus, Geotrichum spp., Rhizopus stolonifer	Addition	
Chinese cinnamon + cinnamon bark	*L. monocytogenes, S. aureus, E. coli, S. Typhimurium*	Addition	(Ghabraie et al. 2016b)
Cinnamon + tea tree	*A. Niger, A. flavus, A. parasiticus, P. chrysogenum*	Addition	(Hossain et al. 2016)
Eucalyptus + tea tree			
Cinnamon + eucalyptus			
Basil + peppermint			
Thymol + trans-cinnamaldehyde	*Escherichia coli* O157: H7	Addition	(Yuan, Teo, and Yuk 2019)
Thymol + eugenol			
Thymol + vanillin			
Vanillin + eugenol			
Vanillin + carvacrol			
Eugenol + trans-cinnamaldehyde			
Trans-cinnamaldehyde + carvacrol			
Carvacrol + thymol	*Campylobacter jejuni*	Synergism	
	S. aureus, Salmonella, E. coli, Bacillus cereus	Synergism	(Gavaric et al. 2015)
	P. roqueforti, A. niger	Synergism	(Ju et al. 2020)
	Escherichia coli O157: H7	Addition	(Yuan, Teo, and Yuk 2019)
Citral + eugenol	*P. roqueforti, A. niger*	Synergism	(Ju et al. 2020)
Citral + thyme	*P. roqueforti, A. niger*		
Thyme + cinnamaldehyde Citral + carvacrol	*A. niger*		
Cinnamon bark + citronella	*P. corylophilum*	Synergism	(Ji et al. 2019)
Pelargonium asperum + ormenis mixta	*Staphylococcus aureus*	Synergism	(Ouedrhiri et al. 2018)
Eucalyptus caesia Benth + dracocephalum multicaule Montbr & Auch	*Bacillus cereus, Staphylococcus aureus, Listeria monocytogenes*	Synergism	(Hashemi and Jafarpour 2020)
	Escherichia coli, Shigella flexneri, Pseudomonas aeruginosa, Salmonella typhi	Addition	
Rosemary + carvacrol	*Bacillus subtilis*	Synergism	(Fadil et al. 2018)

3.3. Antimicrobial effects of EOs in meat and meat products

Many EOs and their active compounds have been proved with great antimicrobial activities in vitro, individually and in combination (Chouhan, Sharma, and Guleria 2017; Van de Vel, Sampers, and Raes 2019). Lists of the frequently used EOs or active compounds in antimicrobial activity testing used singly and in combination are presented in Tables 1 and 2, respectively.

3.3.1. Effects of individual EOs

Several methods were used to test the antimicrobial capacities of EOs, including disk diffusion, agar wells, agar dilution method, broth dilution, time-kill analysis/survival curves, scanning electron microscopy (Burt 2004). The minimum inhibitory concentration (MIC) is cited by most researchers, defined as the lowest concentration of EOs to completely inhibit the growth (bacteriostatic) of microorganism within a certain time and under specific conditions (Van de Vel, Sampers, and Raes 2019). Dussault, Vu, and Lacroix (2014) reported the broad-spectrum antibacterial activity of oregano (*Thymus capitatus* Hoff.) and thyme (*Thymus vulgaris* and *Thymus zygis* L. var. *gacilis* Boissier) EOs against all groups of bacteria among the tested sixty-seven essential oils, oleoresins, and pure compounds. Chinese cinnamon (*Cinnamomum cassia*) was found to be the most effective EO from 32 EOs against five foodborne and spoilage bacteria with its lowest MIC values (Ghabraie et al. 2016a). Mustard EO and its main component, allyl isothiocyanate, showed a strong antibacterial capacity to foodborne bacteria (Dussault, Vu, and Lacroix 2014; Peng et al. 2014; Turgis et al. 2009). The effectiveness of EOs varies with the distilled parts of plants, plants' origins, and producing seasons (Burt 2004; Dussault, Vu, and Lacroix 2014; Ghabraie et al. 2016a).

Several studies on the effects of EOs on meat and meat products have been performed, showing great antimicrobial abilities for extending the shelf life of products (Calo et al. 2015). Some studies about applications of single EOs in meat and meat products are mentioned in Table 3. Oregano (*Origanum vulgare*), thyme (*Thymus vulgaris*), orange (*Citrus sinensis* var. Valencia) EOs used in the vapor phase had been proved to have good antibacterial activities (Luna-Guevara et al. 2021). The amount of 2000 mg/L of oregano EO reduced most *Salmonella* populations of 1.97 log CFU/g after 144 h storage and was organoleptically acceptable in the attributes of odor, texture, color, and general acceptance of sausages. Sage EO (*Salvia officinalis* L) at concentrations of 0.075 μL/g and 0.1 μL/g significantly reduced the total number of aerobic mesophilic bacteria and inhibited *Salmonella* spp., *Escherichia coli,* and *Listeria monocytogenes* and even resulted in better sensory properties of fresh pork sausages (Šojić et al. 2018). According to Dussault, Vu, and Lacroix (2014), the growth rate of *L. monocytogenes* for hams containing EOs of garlic (*Allium sativum* L.) and red thyme (*Thymus vulgaris* and *Thymus zygis* L. var. *gacilis* Boissier) were not significantly different from the control. However, EOs of oregano (*Thymus capitatus* Hoff.) and Chinese cinnamon (*Cinnamon cassia*) contributed to 19% and 10% growth inhibition of *L. monocytogenes* in hams, respectively. Zhang et al. (2016) observed a reduction of lipids oxidation and a high inhibition of *Pseudomonas* spp. and *Enterobacteriaceae* at both concentrations of 0.1% and 0.5% of black pepper EOs (*Piper nigrum* L.) on fresh pork. da Silveira et al. (2014) displayed that sensory characteristics of the bay leaf EO (*Laurus nobilis* L.) treated fresh Tuscan sausages were found acceptable for both tested concentrations (0.05% and 0.1%). They observed a reduction of the microorganisms (total *coliforms)* by nearly 3 log CFU/g and an extension of the product shelf life by 2 days in the experiments. Kingchaiyaphum and Rachtanapun (2012) showed that kaffir lime peel EO (*Citrus hystrix* DC.) has a stronger antioxidative effect than fingerroot EO (*Boesenbergia pandurata* Roxb.). Then, 10% kaffir lime peel and fingerroot can extend shelf life of Chinese sausages by 5 and 10 days, respectively.

3.3.2. Synergistic effects of EOs

The antimicrobial activity of EOs results from the complex interactions between their compounds such as phenols, alcohols, aldehydes, esters, ethers, or methoxy derivatives (Burt 2004; Jayasena and Jo 2013). The bioactivities of EOs are closely related to the main components; however, many researchers proved the high antimicrobial properties of the EO components when tested separately (Bassolé and Juliani 2012). The interaction between EO compounds includes four possible types of effects: synergistic, additive, no interactive, or antagonistic effects (Burt 2004). An additive effect is defined as the combined effect is equal to the sum of the individual effects. Antagonism is defined as the combined effect is less than the sum of individual effects. Synergism is when the combined substances are greater than the sum of the individual effects, while the no interactive is defined as indifference (Burt 2004). The assessment of the interaction between essential oil components is based on using macro- or micro-dilution techniques, among these techniques, the checkerboard is the most commonly used (Mackay, Milne, and Gould 2000). The fractional inhibitory concentration index (FIC) is defined as the sum of FIC_A and FIC_B as it is shown in Eq. (3), where FIC_A is the MIC of compound A in combination divided by the MIC of compound A alone (A pure), as shown in Eq. (1), and FIC_B the MIC of compound B in combination, divided by the MIC of compound B alone (B pure), as shown in Eq. (2):

$$FIC_A = MIC_A\text{combined}/MIC_A\text{alone} \tag{1}$$

$$FIC_B = MIC_B\text{combined}/MIC_B\text{alone} \tag{2}$$

$$FIC = FIC_A + FIC_B \tag{3}$$

Synergistic effect is defined for FIC ≤ 0.5; additive effect for $0.5 \leq$ FIC ≤ 1; no interaction for $1 <$ FIC ≤ 4 and for FIC > 4, is defined as an antagonistic effect (Ayari et al. 2020).

Oregano (*Origanum vulgare*) and thyme (*Thymus vulgaris*) EOs showed significant synergistic effects to several pathogenic micro-organisms like *A. flavus, A. parasiticus, P. chrysogenum* (Hossain et al. 2016), and *S. Aureus, Salmonella, E. coli, Bacillus cereus* (Gavaric et al. 2015). To be noticed, phenolic monoterpenes and phenylpropanoids (typical strong antimicrobial activities), when combined with other components, were found to be able to increase the bioactivities of these mixtures. Phenolic monoterpenes and phenylpropanoids in combination with other components, were found to increase the bioactivities (Bassolé and Juliani 2012). The combinations of phenolic compounds with monoterpenes alcohols were observed synergistic or additive; for example, the combination of phenolics (thymol, carvacrol, eugenol) was synergistically or additively active against *E. coli* strains (Ayari et al. 2020; Ju et al. 2020; Yuan, Teo, and Yuk 2019).

Combinations could also be used to decrease the quantities of EOs applied in situ and lower the organoleptic impacts of EOs, and then enable to use a broader range of them to treat meat and meat products (Hyldgaard, Mygind, and Meyer 2012). Some studies on the effects of EOs in combinations on meat products are reported in Table 3. The combinations of EOs have been widely applied in fresh meat and processed meat products and showed great biopreservation potential to extend the shelf life. Thanissery and Smith (2014) applied thyme-orange combination at 0.5% to marinade broiler breast fillets and whole wings that significantly reduced the total aerobic and facultative mesophilic numbers on day 1, 7, and 10 compared with the controls. Ghabraie et al. (2016b) conducted experiments of 16 formulations consisting of nisin (12.5–25 ppm), nitrite (100–200 ppm), mixed essential oils (EOs) of Chinese cinnamon (*Cinnamomum cassia*) plus Cinnamon bark (*Cinnamomum verum*) (0.025–0.05%) and mixed of potassium lactate and sodium acetate (1.55–3.1%) with irradiation at 1.5 kGy against *Clostridium sporogenes* in a sausage model and revealed good antibacterial activities of formulations. EOs combination of shirazi-thyme (*Zataria multiflora*), cinnamon (*Cinnamomum zeylanicum*), and clove (*Syzygium aromaticum*) can efficiently act against *P. fluorescens* at low combination doses and decrease the adverse sensory concerns of EOs applied in chicken breast meat stored at 4 °C (Chaichi et al. 2021). Anacardiaceae (*Pistacia lentiscus*) and Lamiaceae (*Satureja montana*) EOs showed synergistic effects to reduce *L. monocytogenes* growth and extend the shelf life of minced meat during refrigerated storage (Djenane et al. 2011). Vasilijević et al. (2019) combined Juniper (*Juniperus communis* L.) and winter savory (*Satureja montana* L.) EOs applied on red wine marinades tested against *L. monocytogenes, Enterobacteriaceae*, lactic acid bacteria, and aerobic heterotrophic mesophyll bacteria. The EO mixtures decreased all the microbial counts during storage and were all sensory acceptable on beef. Menezes et al. (2018) observed that the addition of oregano (*Origanum vulgare*) essential oil enhanced the shelf-life of vacuum-packed cooked sliced ham based on LAB levels and more than 30 days were extended when cooked hams stored at 6 °C comparing to control. Reduced counts of Enterobacteriaceae, total coliform and *Staphylococcus aureus* during ripening were investigated with addition of oregano (*Coridothymus capitatus*) (0.25% v/v) or thyme (*Thymus vulgaris*) (0.25% v/v) EO in Tunisian dry fermented poultry meat sausages (El Adab and Hassouna 2016). Six EOs, basil (*Ocimum basilicum* L), garlic (*Allium sativum* L.), nutmeg (*Myristica fragans*), oregano (*Origanum vulgare*), rosemary (*Rosmarinus officinalis* L) and thyme (*Thymus capitatus* Hoff. et Link), were used at 0.005% and 0.05% separately on dry cured sausages chouriço showing an inhibitory effect against *Salmonella* spp., *Listeria monocytogenes* and *Staphylococcus aureus* along processing (García-Díez et al. 2016).

3.4. Limitations of EOs

The interaction of bioactive compounds with meat product compositions may decrease the effectiveness of the EOs. The fats, proteins, carbohydrates, water content, salts, and food additives as well as environmental determinants like temperature, packaging in vacuum/gas/air affect bacterial sensitivity (Calo et al. 2015; Jayasena and Jo 2013). Meat products contain high fat and protein that could dramatically decrease the antimicrobial properties of EOs due to their high binding capacity to volatile compounds of EOs (Sultanbawa 2011). Thereafter, when EOs are applied in meats, it is always required in higher concentrations than in vitro to achieve sufficient antimicrobial activity, which raised the adverse organoleptic problems (Hyldgaard, Mygind, and Meyer 2012; Yuan, Teo, and Yuk 2019). The possible solutions proposed by previous research to solve these challenges by combined synergistic effects of EOs or their bioactive compounds, incorporating volatile components of EOs in films or edible coatings, encapsulation of EOs in polymers of edible, and biodegradable coatings or sachets or into micro- and nanoemulsions (Hassoun and Emir Çoban 2017; Jayasena and Jo 2013; Singh et al. 2019).

4. Encapsulation

Encapsulation is a technology that protects EOs by the action of one or more wall materials that could avoid direct interaction with food components and increase the effectiveness of EOs (Barbosa et al. 2021; Gómez et al. 2018), conduct a control release and mask unpleasant odors to decrease the sensory impact on foods (Gulin-Sarfraz et al. 2021; Nazzaro et al. 2012). Encapsulation can be performed either mechanically (spray-drying) or chemically; chemically by simple or complex coacervation (Castro-Rosas et al. 2017). Essential oils can be encapsulated into biopolymers (Heckert Bastos et al. 2020; Jain, Winuprasith, and Suphantharika 2020), liposomes (Kamkar et al. 2021; Wang et al. 2021), micro- or nanoemulsions (Delshadi et al. 2020; Rolim and Ramalho 2021; Yang et al. 2021). Capsules of rosewood (*Aniba rosaeodora*) and cinnamon (*Cinnamon cassia*) EO encapsulated by Tween 80 and poly (butylene adipate-*co*-terephthalate) (PBAT) were also found to have excellent antimicrobial activity against *E. coli*, *Salmonella*, *S. aureus* and *Listeria* (Barbosa et al. 2021). The synthesis of nanoemulsions, microencapsulation and packaging films

Table 3. Applications of EOs in meat preservation.

EOs	Concentrations applied	Tested micro-organisms	Major effects	Types of meat	Storage conditions	References
Oregano (*Origanum vulgare*), thyme (*Thymus vulgaris*), orange (*Citrus sinensis* var. Valencia)	700–2000 mg/L^{-1} of air	*Salmonella enterica*	Reduced the *Salmonella* population in sausages stored until 144 hrs, alter sensory properties	Meat sausage	4 °C	(Luna-Guevara et al. 2021)
Sage (*Salvia officinalis* L.)	0.05 μL/g, 0.75 μL/g, 0.1 μL/g,	Total number of aerobic mesophilic bacteria, *Salmonella* spp., *Escherichia coli and Listeria monocytogenes*	Reduced total number of aerobic mesophilic bacteriaand inhibited *Salmonella* spp., *Escherichia coli* and *Listeria monocytogenes*, better sensory properties	Fresh pork sausage	3 ± 1 °C, under dark conditions, for 8 days.	(Šojić et al. 2018)
Bay leaf (*Laurus nobilis* L.)	0.05 g/100 g or 0.1 g/100 g	*Psychrotrophs*, *Mesophiles*, Lactic acid bacteria and Total *coliforms*	Reduced the population of total coliforms (2.8 log CFU/g) and to extend the product shelf life for two days	Tuscan sausage	7 °C for 14 days	(da Silveira et al. 2014)
Garlic (*Allium sativum* L.), oregano (*Thymus capitatus* Hoff.), thym (red) (*Thymus vulgaris* and *Thymus zygis* L. var. *gacilis* Boissier), Chinese cinnamon (*cinnamon cassia*)	500 ppm (0.05% v/w)	*L. monocytogenes*	A reduction of the growth rate by 19 and 10% was observed when oregano and cinnamon cassia EOs were respectively added in ham at a concentration of 500 ppm.	Ham	4 °C for 35 days	(Dussault, Vu, and Lacroix 2014)
Black pepper essential oil (*Piper nigrum* L.)	0, 0.1 and 0.5%, v/v	*Pseudomonas* spp., *Enterobacteriaceae*	Inhibition of *Pseudomonas* spp., *Enterobacteriaceae*	Fresh pork	4 °C for 9 days	(Zhang et al. 2016)
Thyme and orange	0.5%	Total aerobic and facultative mesophiles	Extended shelf life	Broiler breast fillets and whole wings	Vacuum tumbling, 4 °C	(Thanissery and Smith 2014)
Chinese cinnamon (*Cinnamomum cassia*), Cinnamon bark (*Cinnamomum verum*)	0.025–0.05%	*Clostridium sporogenes*	Reduced *Clostridium sporogenes*	Pork sausage	4 °C	(Ghabraie et al. 2016b)
Shirazi-thyme (*Zataria multiflora*), cinnamon (*Cinnamomum zeylanicum*), and clove (*Syzygium aromaticum*)	20 mg kg^{-1}	*P. fluorescens*	Reduced *P. fluorescens, extend shelf life*	Chicken breast meat	4 °C for 12 days	(Chaichi et al. 2021)
Anacardiaceae (*Pistacia lentiscus*), Lamiaceae (*Satureja montana*)	*S. montana* 0.06%, *P. lentiscus* 0.20%	*Listeria monocytogenes*	Synergy, reduction of *Listeria monocytogenes*, extend shelf life	Minced beef	5 ± 1 °C	(Djenane et al. 2011)
Juniper (*Juniperus communis* L.) and winter savory (*Satureja montana* L.)	0.25% *J. communis* EO; 0.125% *S. montana* EO	*Listeria monocytogenes, Enterobacteriaceae*, aerobic heterotrophic mesophyll bacteria, lactic acid bacteria	Reduction of tested strains, extend shelf life	Red wine-marinated beef	4 °C for 15 days	(Vasilijević et al. 2019)
Oregano (*Origanum vulgare*)	0.4% (v/w)	LAB natural microbiota	Decreased growth rates of LAB, extend shelf-life	Vacuum-packed cooked sliced ham	6, 12, 15, 20 and 25 °C for 45 days	(Menezes et al. 2018)
Oregano (*Coridothymus capitatus*), thyme (*Thymus vulgaris*)	0.25% (v/v) each	Enterobacteriaceae, total coliform, *Staphylococcus aureus*	Reduced the Enterobacteriaceae counts, total coliform counts and *Staphylococcus aureus* counts	Tunisian dry fermented poultry meat sausage	0, 7, 14, 21, 28 days during ripeing	(El Adab and Hassouna 2016)
Basil *(Ocimum basilicum L),* garlic *(Allium sativum L.),* nutmeg *(Myristica fragans),* oregano *(Origanum vulgare),* rosemary *(Rosmarinus officinalis L)* and thyme *(Thymus capitatus* Hoff. et Link*)*	0.005% and 0.05%	*Salmonella* spp., *Listeria monocytogenes, Staphylococcus aureus*	Inhibition of *Salmonella* spp., *Listeria monocytogenes, Staphylococcus aureus,* shorten the drying period	Dry cured sausage chouriço	0, 3, 8, 15, 21 days during ripeing	(García-Díez et al. 2016)

applied in food preservation are widely reviewed (Davarcı et al. 2017; Kfoury et al. 2019; Prakash et al. 2018; Vishwakarma et al. 2016). A summary of some experiments carried out on encapsulation of EOs is presented in Table 4.

4.1. Nanoparticles

Nanoencapsulation could be a way to develop closer interactions between antimicrobial components and micro-organisms (Hyldgaard, Mygind, and Meyer 2012). Nanoparticles (NPs) are nano-vehicles with particle sizes below 100 nm (Rehman et al. 2019). Several techniques have been used to achieve natural biopolymeric NPs, such as nanospray drying, self-assembly, electrospraying, and anti-solvent precipitation (Lammari et al. 2020; Prakash et al. 2018; Rehman et al. 2020a, 2020b).

Hassan et al. (2021) have reported nanoencapsulation of oregano (*origanum syriacum*) EO by chitosan nanoparticles significantly suppress the growth of microbial species. Badawy, Lotfy, and Shawir (2020) indicated that ChMNPs (Monoterpenes loaded with chitosan to form nanoparticles) could be used as a good preservation method for minced meat. The proposed mechanism is that monoterpenes are sensitive to the phospholipid bilayer of the cell membrane of the bacteria causing damages to the enzyme systems and growth inhibition. Furthermore, the positively charged amino groups of chitosan (Ch) would interact with the negatively charged macromolecules on the microbial cell surface to make the leakage of intracellular constituents of the microbial cell. The film-forming property of Ch plays an important role in the antimicrobial property due to Ch as the oxygen barrier. Morsy, Mekawi, and Elsabagh (2018) carried out an experiment in which they reported that lyophilized nanoparticles of pomegranate (*Punica granatum* L.) peel (LPP-NPs) were effective in retarding lipid oxidation and improving the microbial quality and cooking characteristics of meatballs. Ghaderi-Ghahfarokhi et al. (2017) demonstrated that cinnamon (*Cinnamomum zeylanicum* L.) essential oil-incorporated chitosan nanoparticles (CEO-CSNPs) reduced the microbial population of beef patties, lipid oxidation, and improved consumer acceptance. Then, Ghaderi-Ghahfarokhi et al. (2016) investigated that thyme (*Thymus vulgaris* L.) essential oil (TEO) loaded chitosan nanoparticles (CS-NP-TEO) exhibited several distinct advantages of improving the microbial, chemical, and sensory quality during storage of beef burgers.

4.2. Microencapsulation

Microencapsulation could be a promising method to pack the active and/or sensitive components such as EOs as the core into a wall matrix that allows a controlled release and avoids contact with the environment (Castro-Rosas et al. 2017; Hashim et al. 2019; Yostawonkul et al. 2021). Microencapsulation could be achieved using different methods, such as spray-drying, simple and complex coacervation, extrusion, and precipitation (Hashim et al. 2019). The encapsulating materials, such as sodium alginate (sod-Alg), chitosan (Ch), and carboxymethyl cellulose (CMC), are essential for the formation of an effective system (Fadel et al. 2020). Thyme *(Thymus zygis)* and rosemary *(Rosmarinus officinalis)* EO encapsulated in chitosan which was applied on dry fermented sausages as coatings, showed inhibition to molds and yeasts during 3-month storage (Demirok Soncu et al. 2020).

The encapsulation of bioactive compounds into calcium alginate microspheres or beads is arousing more attention presently, which is affected by ionic gelation of the calcium in the alginate droplets and their conversion into hydrogel beads (Davarcı et al. 2017). Fadel et al. (2020) conducted a comparative study on the microencapsulation of 10 commercial EOs into alginate beads. They found that the microencapsulation in the sodium alginate and chitosan improved the antioxidant activity and phenolic content of the encapsulated clove (*Syzygium aromaticum*) EO compared with carboxymethyl cellulose. Huq et al. (2015) presented a study in which microencapsulation of antimicrobials (EOs and nisin) combined with γ-irradiation treatments showed synergistic antimicrobial effect during storage on ready to eat (RTE) meat products. The micro-encapsulation had increased the bacterial radiosensitivity (RS) of oregano (*Origanum compactum*) and cinnamon (*Cinnamomum cassia*) both with nisin by 39 and 113% compared to free ones. Criado et al. (2019) has found that introduction of cellulose nanocrystals (CNCs) from 0 to 30% in alginate beads exhibited an increase of thyme (*Thymus vulgaris*) EO loading capacity and a longer continuous release period was noticed when thyme EO was 3% in beads. The microbeads contributed to a 2 log reduction of *L. innocua* during more than 10 days storage as compared to the control and a synergy between microbeads and irradiation was observed.

4.3. Active packaging

Essential oil incorporation in polymers can lead to physical changes such as the film structure, water barrier properties, and transparency, whereas it may provide edible films with antioxidant and/or antimicrobial properties (Atarés and Chiralt 2016). There are uses of packaging films and coatings in the active packaging technology (Ribeiro-Santos et al. 2017). Using the technology of incorporating EOs in functional packaging films can reduce the diffusion rate of EOs into food products, conduct a controlled release of active compounds to product surface that extend the shelf life of products without affecting the organoleptic properties (Hyldgaard, Mygind, and Meyer 2012; Pateiro et al. 2021) and help to maintain temperature, moisture, and quality control of the food (Sharma et al. 2021). Biopolymers like proteins and polysaccharides, due to their nature of biodegradability, are drawing great interests in using for antimicrobial packaging films (Cha and Chinnan 2004; Vieira et al. 2011). The mobility of volatile compounds of EOs introduced in the polymer matrix is a key point for understanding release mechanisms (Wicochea-Rodríguez et al). The mechanism of the action of active packaging could be direct contact with food or through mass transfer to the headspace

Table 4. Applications of EOs encapsulated in meat and meat products.

EOs	Concentrations applied	Encapsulation and types	Tested micro-organisms	Major effects	Types of meat	Storage conditions	References
Anise (*Pimpinella anisum L.*), caraway (*Carum carvi L.*), Nutmeg (*Myristica fragrans*)	Anise 0.5%, caraway 1%, nutmeg 1%	Manihot esculenta and Carrageenan functionized with anise, caraway, film	Total plate count, *psychrophilic* count, *Coliform* and, yeast and mold	Total plate count, psychrophilic count and, yeast and mold count were also significantly ($P < 0.01$) lower in treatment groups	Chicken nuggets	$4 \pm 1\,°C$,15 days	(Bharti et al. 2020)
Thyme (*Thymus vulgaris*)	1–3%	Alginate, cellulose nanocrystals (CNCs), beads	*L. innocua* and mesophilic total flora (MTF)	Eliminated *L. innocua* and reduce the mesophilic total flora (MTF)	Ground lean pork	4 °C for 14 days	(Criado et al. 2019)
Thyme	8:2 (silk fibroin nanofibers: plasma-thyme EO)	Silk fibroin nanofibers	*Salmonella* typhimurium	After combined treatment, the number of *Salmonella* Typhimurium in chicken meat and duck meat decreased by 6.1 and 6.06 Log CFU/g compared with control group at 25 °C, respectively.	Poultry meat (chicken and duck)	4 or 25 °C for 7 days	(Lin, Liao, and Cui 2019)
Garlic (*Allium sativum*)	Garlic essential oil or nanoencapsulated garlic EO(2% v/v)	Chitosan, whey protein, film	Aerobic plate count, lactic acid bacteria, psychrotrophic bacteria, *Staphylococcus aureus*, coliforms	Retarded the growth of main spoilage bacterial groups l(aerobic plate count 3.69 log CFU/g) compared to the control	Vacuum-packed sausages	4 °C, 50 days	(Esmaeili et al. 2020)
Thyme *(Thymus zygis)*, rosemary *(Rosmarinus officinalis)*	1%	Chitosan, coating	Aerobic total viable count (TVC), lactic acid bacteria (LAB), Gram(+) catalase(+) cocci, *Enterobacteriaceae* and mold/yeast	Retarded fungal mycelium development on the casing.	Dry-fermented sausages	4 °C, 3 months	(Demirok Soncu et al. 2020)
Tarragon (Artemisia dracunculus L.)	Mass ratios of chitosan to Tarragon EO (1:0, 1:0.2, 1:0.4, 1:0.6, 1:0.8 and 1:1)	Chitosan, coating	Total viable count	Inhibited the quality deterioration	24 h postmortem fresh pork slices	4 °C for 16 days	(Zhang et al. 2020)
Satureja (*Satureja khuzestanica*)	1% v/v, proper amounts of free EO and SKEO-loaded nanoliposomes	Chitosan, coating	Total Viable Count (TVC), Lactic Acid Bacteria (LAB) and *Pseudomonads* (PBC)	Slowed down the microbial growth significantly	Lamb meat	°C for 20 days	(Pabast et al. 2018)
Rosemary (*Rosmarinus officinalis*)	5000 mg/L	Chitosan-benzoic acid (CS-BA), nanogel	*Salmonella typhimurium*	Nanogel-encapsulation led to higher antibacterial activity against *Salmonella typhimurium* on beef.	Beef cutlet	4 °C for 1, 4, 8, and 12 days	(Hadian et al. 2017)
Pomegranate (*Punica granatum* L.) peel extracts	1 and 1.5%	Lyophilized nanoparticles	Total viable bacterial count, psychrophilic bacteria, and lipolytic bacteria	Effective antioxidant and antimicrobial properties, increased sensory acceptabilities.	Meatballs of minced beef meat	4 °C for 15 days	(Morsy, Mekawi, and Elsabagh 2018)
Clove (*Syzygium aromaticum*)	2 mg/g beef	Chitosan (CS)-Myristic acid (MA) nanogel	*S. entericaser. Enteritidis*	Nanogel had more efficiency in controlling the investigated pathogen than the free CEOs	Beef cutlets	4 °C for 12 days	(Rajaei et al. 2017)
	(0.1% of encapsulated CEO	Chitosan, nanoparticles	*S. aureus*, total mesophilic aerobic	The encapsulation increased the antimicrobial abilities	Beef patties	4 °C for 8 days	(Ghaderi-Ghahfarokhi et al. 2017)

Cinnamon (*Cinnamomum zeylanicum* L.)			viable count (TMVC), *Enterobacteriaceae*, yeasts and molds (Y&M) and lactic bacteria (LAB)				
Thyme (*Thymus vulgaris* L.)	Chitosan	0.05 or 0.1% of encapsulated thyme EO, nanoparticles	*S. aureus* *Enterobacteriaceae*	Encapsulation process improved the shelf life, maintained antimicrobial activities during storage.	Beef burgers	4 °C for 8 days	(Maryam Ghaderi-Ghahfarokhi et al. 2016)
Jabuticaba (*Myrciaria cauliflora*) extract (JE)	2 and 4% of MJE	Maltodextrin, microencapsulation	Aerobic mesophiles, Aerobic psychrotrophics, Lactic acid bacteria, thermotolerants coliforms and *S. aureus*	The extract had no positive effect on microbial stability during storage.	Fresh sausages	1 ± 1 °C for 15 days	(Baldin et al. 2016)
Oregano (*Origanum compactum*) or Cinnamon (*Cinnamomum cassia*)	EOs in alginate-CNC microbeads was 250 μg/ml	Alginate-CNC, microencapsulation	*L. monocytogenes*	Microencapsulation significantly ($P \leq 0.05$) improved the radiosensitivity of *L. monocytogenes*. Microencapsulated oregano and cinnamon essential oil in combination with nisin showed the highest bacterial radiosensitization 2.89 and 5, respectively, compared to the control.	Ready-to-eat cooked ham.	4 °C for 35 days	(Huq et al. 2015)

inside the package (Ribeiro-Santos et al. 2017). The antimicrobial effectiveness could depend on the diffusion of active agents onto the food surface through the headspace from the packaging, sachet, coating, or pad (Marturano et al. 2019). The non-contact approach allows a more slow release of aromatic compounds, prolongs the efficiency period, and decreases the toxic level (Ribeiro-Santos et al. 2017; Varghese, Siengchin, and Parameswaranpillai 2020).

Clove and oregano EOs incorporated with palm oil in fish gelatin formed biodegradable packaging film showing antimicrobial and antioxidant activities (da Silva e Silva et al. 2021). Esmaeili et al. (2020) showed that the chitosan film containing nano encapsulated garlic EO exhibited the best microbiological and chemical results. Pabast et al. (2018) highlighted that nano-encapsulation of Satureja EO coated in chitosan contributed to the sensory and microbial qualities and extension of shelf-life of lamb meat during chilled storage. Zhang et al. (2020) found that nano-encapsulation of tarragon EO (TEO) enabled the controlled release of the active compounds on the surface of pork samples and a chitosan-gelatin coating containing encapsulated TEO inhibited lipid oxidation, microbial growth, and improved sensory attributes that extended the shelf life of fresh pork slice by 8 days more than the control.

5. Conclusions

Meat and meat products are sufficient in nutrients that are highly conducive for the growth of spoilage and pathogenic micro-organisms. Esssential oils, as clean-label alternatives, can avoid the carcinogenic and toxic problems caused by synthetic food additives. The biological activity of EOs is intently related to the bioactive compounds of EOs, especially phenolic compounds, which can interact with cell membranes, affect permeability, and leak cell contents. Several EOs are observed to have synergistic effects eliminating or delaying the growth of micro-organisms. The most common contradictory and tricky problem of applying EOs in food products is the maintenance of organoleptic properties of food products with relatively low doses of EOs at which EOs still show high antimicrobial abilities against micro-organisms. Generally, a higher concentration of EOs is required for food models, which usually leads to other unpleasant odors and tastes. Encapsulating EOs into one or more wall materials that carry, delivers, and release EOs controllably is one of the novel technologies to solve this problem. The use of combination of EOs, encapsulation, nisin, irradiation, high hydrostatic pressure, modified atmosphere packaging, etc., are novel technologies to be applied for safety and quality of meat and meat products. Moreover, with the trending use of EOs, it is necessary to develop the regulations including the maximum permissible limits, toxicity studies for food preservation.

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