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Advances and perspectives on the application of essential oils in food packaging films, coatings, and nanoencapsulated materials

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ABSTRACT: Natural additives, particularly essential oils, have gained widespread recognition for their role in enhancing the attributes of natural edible polymers. Comprising a wealth of hydrophobic and volatile compounds, essential oils exhibit notable antioxidant and antimicrobial properties owing to their rich composition of terpenes and aromatic constituents. This review underscores the multifaceted biological properties of essential oils, encompassing their incorporation into films, edible coatings, and nanoencapsulated materials. The effect of utilizing several essential oils as natural additives in combination with different raw materials and plasticizers was compared to the evaluation of their impact on the material properties of films and edible coatings, offering an in-depth analysis of the specific essential oil variants featured in the recent literature. Among the essential oils reviewed, those derived from clove, cinnamon, and oregano emerge as the predominant choices, representing some of the most promising natural additives for biodegradable packaging. Nanoencapsulation techniques have also expanded the role of essential oils in sustainable food packaging by increasing their stability.

Key words: natural additive, foods, biodegradable, biopolymers.

INTRODUCTION

The importance of packaging in the food industry goes beyond product storage. Packages must act as a barrier against factors related to product degradation, for quality maintenance and conservation (Hamann et al. 2021). Synthetic polymeric materials constitute over 40% of the food packaging. However, they can cause environmental problems due to the gas emissions and the contamination of water bodies and landfills. Microplastics can represent a potential risk to life, especially when entering the food chain (Ahmad and Sarbon 2021, Filiciotto and Rothenberg 2020, Shankar and Rhim 2020).

Although the complete replacement of traditional petroleum-based plastics with biodegradable polymeric materials is unpractical nowadays, the application of these active biodegradable materials to food packaging appears to be feasible, at least in certain areas, such as food packaging (Ataei et al. 2020), to reduce the environmental impact of the massive use of synthetic plastics (Mahmud et al. 2024).

Biodegradable films have the same function as conventional films used as packaging. They protect food against external agents and provide a barrier against the permeability of water, gases, and light (Paulo et al. 2021). The presence of natural antimicrobial agents can confer antimicrobial activity to these films (Silva, R. S. et al. 2020, Hamann et al. 2021). In this context, various types and combinations of biomolecules, e.g., polysaccharides, proteins, and lipids have been widely used for their excellent film formality and adequate structure, mechanical, and antimicrobial properties (Jamróz and Kopel 2020, Liyanapathiranage et al. 2023). Additionally, films are produced from polyhydroxyalkanoates (PHA) and polylactides (PLA). PHAs are natural thermoplastics that occur in a wide range of bacteria, while PLA are obtained through the polymerization of lactic acid, which is primarily produced via the fermentation of sugars derived from renewable resources such as corn and sugarcane (dos Santos et al. 2020, Filiciotto and Rothenberg 2020).

Essential oils (EOs) are natural substances obtained from aromatic plants and have antimicrobial and antioxidant capacity. They are non-toxic and have good acceptability among consumers. Moreover, the content of 25 mg of pure EO is recommended for human consumption (Baudoux 2018). However, these oils are volatile, and oxidizable, and their hydrophobic compounds have a strong odor. Therefore, their direct use is limited, as they can cause changes in the flavor of fruits and vegetables (Alves et al. 2022, Cai, C. et al. 2020, Rezende et al. 2020, Zhang et al. 2022). EOs can be also incorporated to films and coverings as natural antimicrobial and antioxidant agents (Khaneghah et al. 2018). These systems using EOs prevent microbial growth and spoilage of food products through the controlled release of antimicrobial substances, including the essential oil from packaging materials. The active packaging system also increases food stability and reduces the amount of chemicals used in the packaging system (Bangar et al. 2022). Several authors presented the EOs as natural additives in films, coatings, or nanoencapsulated as promising to replace the chemical additives.

Different biological properties of EOs were related mainly to antioxidant, antimicrobial (antibacterial and antifungal), and larvicide activities, contributing to the increase in the shelf life of food products (Lima et al. 2021, Bangar et al. 2022). Other biological properties reported for EOs are antiviral, antiseptic, immunostimulant, anti-inflammatory, analgesic, antihistamine, anticatarrhal, litholytic, antispasmodic, antiarrhythmic, and antilithiasic (Baudoux 2018). Table 1 presents some of their main applications, with an indication of whether they are suitable for ingestion, depending on their chemical composition.

Table 1. Characteristics and properties of essential oils.

Popular name	Scientific name	Ingestion	Non ingestion	Biochemical family	Properties
Balsam fir	*Abies balsamea*	X		Sesquiterpene; terpene	Antifungal, antibacterial, antiviral
Celery	*Apium graveolens*	X		Sesquiterpene; phthalide	Antioxidant, tonic, sedative
Rosemary	*Salvia rosmarinus*	X		Terpene ketone; terpene oxide; terpene ester	Antioxidant, anti-inflammatory, antimycotic, antimicrobial, healing, analgesic/refreshing, anti-dandruff, mental stimulant
Garlic	*Allium sativum*	X		Disulfide; cysteine	Antiviral, antimicrobial, antifungal
Angelica	*Angelica archangelica*	X		Nitrogen compound; cymarin	Antifungal, antibacterial, immunostimulant, antispasmodic, carminative, tonic
Star anise	*Illicium verum*	X		Methyl-ester-phenol	Antiseptic, antiviral, antispasmodic, antioxidant
Bergamot	*Citrus bergamia*	X		Terpene aldehyde; coumarin	Antibacterial, anti-inflammatory
Chamomile	*Matricaria chamomilla*	X		Sesquiterpene alcohol; terpene ketone; terpene ester; sesquiterpene; coumarin	Analgesic, anti-inflammatory, antiseptic, bactericidal, soothing, healing, relaxing, sedative
Cinnamon	*Cinnamomum verum*	X		Phenol; aromatic aldehyde; coumarin	Antibacterial, antifungal, antidiabetic, antioxidant, anti-inflammatory
Lemongrass	*Cymbopogon citratus*		X	Terpene aldehyde	Antibacterial, antifungal, anti-inflammatory, antioxidant, analgesic, anxiolytic
Cardamom	*Elettaria cardamomum*	X		Terpene ester	Antiseptic, stimulant, aphrodisiac, diuretic, muscle relaxant, digestive stimulant, tonic

Continue...

Table 1. Continuation...

Popular name	Scientific name	Ingestion	Non ingestion	Biochemical family	Properties
Cedar	*Cedrela fissilis*		X	Sesquiterpene	Anxiolytic, antiseptic, anti-inflammatory, antispasmodic, antifungal,
Carrot	*Daucus carota*	X		Sesquiterpene alcohol; terpene	Anti-inflammatory, antioxidant, moisturizing, healing
Cypress	*Cupressus sempervirens*		X	Sesquiterpene alcohol; terpene; sesquiterpene	Anti-inflammatory, antifungal, antitussive, antioxidant, antimicrobial
Citronella	*Cymbopogon (lemongrass)*		X	Terpene aldehyde	Anti-infectious, antibacterial, antiseptic, acaricidal
Coriander	*Coriandrum sativum*	X		Terpenic alcohol; terpene	Digestive, antiflatulent, antispasmodic
Copaiba	*Copaifera langsdorffii*	X		Sesquiterpene	Healing, antiseptic, antibacterial, diuretic, anti-inflammatory, expectorant, analgesic, antirheumatic, antidiarrheal
Comin	*Cuminum cyminum*	X		Aromatic aldehyde	Antioxidant, antiseptic, antispasmodic, antitoxic, aphrodisiac, bactericidal, carminative, depurative, digestive, diuretic, emmenagogue, larvicide, nervine, stimulant, tonic
Clove	*Eugenia caryophyllata*	X		Phenol; terpene ester	Analgesic, anti-inflammatory, antibacterial, antiparasitic, antifungal, antioxidant, aphrodisiac, antidiabetic, antitumor, antiviral,
Curcuma	*Curcuma longa*	X		Sesquiterpene	Immunostimulants, anti-inflammatory, antalgic, antioxidant, antiallergic, antibacterial, antifungal, antiviral, anticancer
Anise	*Pimpinella anisum*	X		Terpene aldehyde; methyl-ester-phenol	Anticoagulant, antithrombotic, anti-inflammatory, analgesic, sedative
Eucalyptus	*Eucalyptus staigeriana*		X	Phenol; terpenic alcohol; aromatic aldehyde; terpene aldehyde; terpene ketone	Analgesic, antiseptic, antibacterial, antispasmodic, antiviral, expectorant, antipyretic
Fennel	*Foeniculum vulgare*	X		Methyl-ester-phenol	Herbicide, insecticide, antioxidant, antimicrobial
Ginger	*Zingiber officinale*	X		Sesquiterpene	Antiseptic, anti-inflammatory, antioxidant, anti-infective, analgesic, digestive
Geranium	*Pelargonium*	X		Terpenic alcohol; terpene aldehyde; terpene ester	Antioxidants, bactericidal, anti-inflammatory, antiseptic, astringent
Hyssop	*Hyssopus officinalis*	X		Terpene ketone; terpenic oxide; methyl-ester-phenol	Expectorant, mucolytic, anti-asthmatic, antibacterial, antifungal, antiviral
Spearmint	*Mentha spicata*	X		Terpenic alcohol; terpene ketone; terpenic oxide; terpene ester	Antimicrobial, decongestant, digestive, anti-inflammatory, antioxidant, analgesic, tonic, disinfectant, anticonvulsant
Jasmine	*Jasminum officinale*		X	Terpene ester	Antidepressant, anti-inflammatory, antiseptic, healing, sedative, moisturizing, anxiolytic
Lavender	*Lavandula spica*	X		Terpenic alcohol; terpene ketone; terpene ester; terpene; coumarin	Antispasmodic, soothing, relaxing, sedative, anti-inflammatory, analgesic, healing, antihypertensive, anti-infectious, antifungal, antiseptic, bactericidal, skin regenerating

Continue...

Table 1. Continuation...

Popular name	Scientific name	Ingestion	Non ingestion	Biochemical family	Properties
Orange	*Citrus × sinensis*	X		Terpene; coumarin	Antioxidant, digestive, antipyretic, bactericide, antiseptic, respiratory decongestant, antilipid, anti-stress
Key lime	*Citrus × aurantiifolia*	X		Terpene; coumarin	Antiseptic, antiviral, astringent, bactericidal, disinfectant, febrifuge, hemostatic, restorative, tonic
Lemon	*Citrus limon*	X		Terpene; coumarin	Antibacterial, antifungal, antiviral, astringent, anticoagulant, immunosuppressive, antistress, hypotensive
Laurel	*Laurus nobilis*	X		Methyl-ester-phenol; terpene ester; terpenic oxide; lactone	Bactericidal, fungicidal, anti-infectious, analgesic
Basil	*Ocimum basilicum*	X		Methyl-ester-phenol	Antiseptic, bactericidal, antiviral, fungicidal, anti-inflammatory, analgesic
Marjoram	*Origanum majorana*	X		Terpenic alcohol	Anxiolytic, analgesic, antispasmodic, tonic
Lemon balm	*Melissa officinalis*	X		Terpene aldehyde; coumarin	Antispasmodic, analgesic, diaphoretic, mild laxative, antiviral, antibacterial, choleretic, carminative, expectorant, antipyretic, healing
Myrrh	*Commiphora myrrha*	X		Sesquiterpene	Antifungal, tonic, sedative, antimicrobial, astringent, anti-inflammatory, antiseptic, aromatic, healing, deodorant, disinfectant, anesthetic
Spikenard	*Nardostachys jatamansi*		X	Terpene; sesquiterpene	Anti-inflammatory, antipyretic, bactericidal, deodorant, fungicidal, laxative, sedative, cardiac and nervous system tonic
Frankincense	*Boswellia carterii*		X	Terpene; sesquiterpene; ketone	Analgesic, anti-inflammatory, expectorant, soothing
Oregano	*Origanum vulgare*	X		Phenol; sesquiterpene	Antifungal, antiviral, antibacterial, immunostimulant, analgesic, antioxidant
Palmarosa	*Cymbopogon martinii*	X		Terpenic alcohol	Antigenotoxic, antioxidant, antiseptic, antiviral, bactericidal, cytophylactic, febrifuge, aphrodisiac, antifungal, aromatic, soothing, healing, stimulant
Black sprice	*Picea mariana*		X	Terpene	Anti-inflammatory, analgesic, expectorant, astringent, healing, detoxifying, deodorant, bactericidal, fungicide, antiseptic for the genitourinary system
Black pepper	*Piper nigrum*	X		Sesquiterpene	Analgesic, antiseptic, antispasmodic, carminative, detoxifying, diuretic, antipyretic, laxative, rubefacient, stomachic
Damask rose	*Rosa × damascena*		X	Nitrogen compound; sulfur compound	Antidepressant, anti-inflammatory, antiseptic, antispasmodic, aphrodisiac, bactericidal, cholagogue, depurative, diuretic, emmenagogue, hemostatic, liver and stomach stimulant, laxative, sedative, spleen, tonic
Sage	*Salvia officinalis*	X		Sesquiterpene alcohol; terpene ketone; sulfur compound	Relaxing, astringent, antiseptic, aromatic, cell regenerator, antidepressant, antispasmodic
Indian sandalwood	*Santalum album*	X		Sesquiterpene alcohol	Anxiolytic, antiseptic, anti-inflammatory, antispasmodic, aphrodisiac, expectorant, hypotensive

Continue...

Table 1. Continuation...

Popular name	Scientific name	Ingestion	Non ingestion	Biochemical family	Properties
Mandarin orange	*Citrus reticulata*	X		Terpene	Antidepressant, antispasmodic, carminative
Tea tree	*Melaleuca alternifolia*		X	Terpenic alcohol; terpene aldehyde	Curative, antiseptic, analgesic, anti-inflammatory, antispasmodic, bactericidal, healing, expectorant, fungicidal, balsamic, antiviral, febrifuge, insecticide, immunostimulant, diaphoretic, parasiticide, vulnerary
Bitter orange	*Citrus aurantium*	X		Terpene	Antidepressant, antiseptic, diuretic, disinfectant, lymphatic stimulant, tonic, anti-infective
Thyme	*Thymus vulgaris*	X		Phenol; terpenic alcohol	Antibacterial, fungicidal, antiviral, analgesic
Thuja	*Thuja occidentalis*		X	Terpene ketone	Immunostimulant, antiviral, antimycotic
Verbena	*Verbena officinalis*	X		Terpene aldehyde, sesquiterpene alcohol	Antidepressant, analgesic, antispasmodic, fungicide, antiseptic
Wintergreen	*Gaultheria procumbens*		X	Terpene ester	Analgesic, anti-rheumatic, antiseptic
Ylang Ylang	*Cananga odorata*	X		Terpene ester; sesquiterpene	Bactericide, fungicide
Yuzu	*Citrus junos*	X		Terpene	Anxiolytic, anti-inflammatory, antioxidant
Juniper	*Juniperus communis*	X		Terpene	Antioxidant, antiseptic, anti-inflammatory, anti-rheumatic

Source: Adapted from Baudoux (2018).

Edible films, coatings, and nanoencapsulated EOs have packaging properties that protect the inside from the outside, limiting the transport of gases and water vapor between the food product and the environment. The term edible means ingestion together with the food which they are in contact with, which presents the need to be considered safe for humans (dos Santos et al. 2020, Erkmen and Barazi 2018).

Nanotechnological packaging systems are becoming more sophisticated, and, with the increasing development of technologies, it is leading to innovation in the field of smart packaging and used in food preservation and storage. The use of nanomaterials, e.g., in antimicrobial packaging can extend shelf life and delay food spoilage. This process is necessary to reduce the amount of chemicals utilized for food conservation (Junges et al. 2022).

Thus, the aims of this review were to make a compilation of very recent advances obtained in the field of natural agents utilized in the production of biodegradable films for food packaging (Table 2), and to present perspectives about their use by the food industry (Fig. 1).

Table 2. Characterization of biopolymer films containing essential oils.

Essential oil ($g{\cdot}100\ g^{-1}$)	Other compounds ($g{\cdot}100\ g^{-1}$)	Sw (%)	WVP ($g{\cdot}mm{\cdot}d^{-1}{\cdot}kPa^{-1}{\cdot}m^{-2}$)	TS (Mpa)	EB (%)	Reference
Anise, 0.5	Chitosan, 2.0 in acetic acid, 1.0; glycerol, 1.0; Tween 80, nd	21.66 ± 0.51	21,168*	15.85 ± 0.06	7.81 ± 0.04	Mahdavi et al. (2017)
Anise, 1.0	Chitosan, 2.0 in acetic acid, 1.0; glycerol, 1.0; Tween 80, nd	16.14 ± 0.25	19,613*	16.75 ± 0.56	9.24 ± 0.08	Mahdavi et al. (2017)
Anise, 1.5	Chitosan, 2.0 in acetic acid, 1.0; glycerol, 1.0; Tween 80, nd	12.01 ± 0.65	9,504*	18.71 ± 0.32	10.61 ± 0.35	Mahdavi et al. (2017)
Anise, 2.0	Chitosan, 2.0 in acetic acid, 1.0; glycerol, 1.0; Tween 80, nd	9.49 ± 0.32	7,776*	21.38 ± 0.26	12.32 ± 0.05	Mahdavi et al. (2017)

Continue...

Table 2. Continuation...

Essential oil (g·100 g^{-1})	Other compounds (g·100 g^{-1})	Sw (%)	WVP (g·mm·d^{-1}·kPa^{-1}·m^{-2})	TS (Mpa)	EB (%)	Reference
Apricot kernel, 0.125	Chitosan, 2.0 in acetic acid, 1.0; Tween 80, 0.2	12.50 ± 1.67	48.0	13.92 ± 0.70	11.03 ± 1.34	Priyadarshi et al. (2018)
Apricot kernel, 0.25	Chitosan, 2.0 in acetic acid, 1.0; Tween 80, 0.2	8.82 ± 1.21	46.4	14.41 ± 0.81	5.46 ± 0.59	Priyadarshi et al. (2018)
Apricot kernel, 0.5	Chitosan, 2.0 in acetic acid, 1.0; Tween 80, 0.2	6.52 ± 0.95	29.5	17.67 ± 0.98	4.02 ± 0.14	Priyadarshi et al. (2018)
Apricot kernel, 1.0	Chitosan, 2.0 in acetic acid, 1.0; Tween 80, 0.2	4.76 ± 1.03	26.2	19.36 ± 1.06	3.76 ± 0.43	Priyadarshi et al. (2018)
Basil, 1.0	Chitosan, 3.0 in hydrochloric acid, 0.3; glycerol, 0.9	nd	nd	13.0 ± 4.3	23.0 ± 0.7	Amor et al. (2021)
Basil, 2.0	Chitosan, 3.0 in hydrochloric acid, 0.3; glycerol, 0.9	nd	nd	10.8 ± 1.7	22.0 ± 5.4	Amor et al. (2021)
Basil, 3.0	Chitosan, 3.0 in hydrochloric acid, 0.3; glycerol, 0.9	nd	nd	10.5 ± 2.3	22.0 ± 4.8	Amor et al. (2021)
Bergamot, 0.15	Unicorn leatherjacket skin gelatin, 3.0; glycerol, 0.6; Tween 20, 0.0225	93.37 ± 0.57	10.9 ± 0.2	36.34 ± 3.14	8.76 ± 3.45	Ahmad et al. (2012)
Bergamot, 0.3	Unicorn leatherjacket skin gelatin, 3.0; glycerol, 0.45; Tween 20, 0.045	93.14 ± 0.37	16.2 ± 0.3	30.8 ± 6.41	7.33 ± 2.12	Ahmad et al. (2012)
Bergamot, 0.45	Unicorn leatherjacket skin gelatin, 3.0; glycerol, 0.3; Tween 20, 0.0675	93.07 ± 0.45	16.8 ± 0.5	27.94 ± 3.34	7.18 ± 4.60	Ahmad et al. (2012)
Bergamot, 0.6	Unicorn leatherjacket skin gelatin, 3.0; glycerol, 0.15; Tween 20, 0.09	90.04 ± 0.46	16.2 ± 0.9	27.96 ± 7.24	3.70 ± 2.04	Ahmad et al. (2012)
Bergamot, 0.75	Unicorn leatherjacket skin gelatin, 3.0; Tween 20, 0.1125	89.82 ± 0.96	15.9 ± 1.1	23.75 ± 6.85	3.06 ± 2.00	Ahmad et al. (2012)
Bergamot, 0.5	Chitosan, 1.0 in acetic acid, 0.5	nd	112.5*	65 ± 10	7 ± 4	Sánchez-González et al. (2010)
Bergamot, 1.0	Chitosan, 1.0 in acetic acid, 0.5	nd	74.3*	63 ± 21	5.5 ± 0.7	Sánchez-González et al. (2010)
Bergamot, 2.0	Chitosan, 1.0 in acetic acid, 0.5	nd	79.5*	50 ± 8	6 ± 2	Sánchez-González et al. (2010)
Bergamot, 3.0	Chitosan, 1.0 in acetic acid, 0.5	nd	56.2*	22 ± 8	1.7 ± 0.4	Sánchez-González et al. (2010)
Black pepper, 0.05	Gelatin, 5.0; cloisite Na^+, 0.05; Tween, 0.0375	nd	14.64*	64.05 ± 2.61	7.77 ± 0.91	Saranti et al. (2021)
Caraway, 1.0	Chitosan, 1.0 in acetic acid, 1.0	18.14 ± 4.03	3.36*	44.47 ± 4.40	31.53 ± 4.28	Hromiš et al. (2015)
Caraway, 1.0	Chitosan, 1.0 in acetic acid, 1.0; beeswax, 1.8; Tween 20, 0.5	17.33 ± 1.98	4.02*	8.78 ± 0.88	14.74 ± 2.96	Hromiš et al. (2015)
Caraway, 1.0	Chitosan, 1.0 in acetic acid, 1.0; beeswax, 3.6; Tween 20, 0.5	9.08 ± 1.68	4.10*	3.90 ± 0.29	10.97 ± 1.48	Hromiš et al. (2015)
Caraway, 1.0	Chitosan, 1.0 in acetic acid, 1.0; beeswax, 5.4; Tween 20, 0.5	6.11 ± 0.95	5.08*	2.75 ± 0.46	6.04 ± 1.67	Hromiš et al. (2015)
Caraway, 1.0	Chitosan, 1.0 in acetic acid, 1.0; beeswax, 7.2; Tween 20, 0.5	1.86 ± 0.40	3.61*	2.14 ± 0.14	4.92 ± 1.22	Hromiš et al. (2015)
Caraway, 1.0	Chitosan, 1.0 in acetic acid, 1.0; beeswax, 9.0; Tween 20, 0.5	2.21 ± 1.47	3.36*	2.04 ± 0.25	5.55 ± 1.62	Hromiš et al. (2015)
Cedarwood, 0.045	Sugar beet lignocellulose, 0.9; glycerol, 0.1; Span 80, 0.01	25.9 ± 1.5	22.5 ± 0.9	47.4 ± 5.0	11.4 ± 1.6	Shen and Kamdem (2015a)

Continue...

Table 2. Continuation...

Essential oil (g·100 g⁻¹)	Other compounds (g·100 g⁻¹)	Sw (%)	WVP (g·mm·d⁻¹·kPa⁻¹·m⁻²)	TS (Mpa)	EB (%)	Reference
Cedarwood, 0.09	Sugar beet lignocellulose, 0.9; glycerol, 0.1; Span 80, 0.01	24.9 ± 0.9	21.6 ± 0.9	36.1 ± 5.1	9.9 ± 1.5	Shen and Kamdem (2015a)
Cedarwood, 0.135	Sugar beet lignocellulose, 0.9; glycerol, 0.1; Span 80, 0.01	21.8 ± 1.2	19.9 ± 0.9	28.1 ± 2.9	6.4 ± 0.5	Shen and Kamdem (2015a)
Cedarwood, 0.1	Chitosan, 1.0 in acetic acid, 1.0; Tween 80, 0.001	nd	27.6*	36.54 ± 3.78	25.80 ± 1.53	Shen and Kamdem (2015b)
Cedarwood, 0.2	Chitosan, 1.0 in acetic acid, 1.0; Tween 80, 0.002	nd	23.3*	28.47 ± 1.42	18.33 ± 2.17	Shen and Kamdem (2015b)
Cedarwood, 0.3	Chitosan, 1.0 in acetic acid, 1.0; Tween 80, 0.003	nd	13.8*	22.29 ± 0.83	5.07 ± 1.01	Shen and Kamdem (2015b)
Cinnamon, 0.025	Soy protein isolate, 1.0; glycerol, 0.3	nd	15.36 ± 0.48	11 ± 4	3.4 ± 1.8	Atarés et al. (2010)
Cinnamon, 0.05	Soy protein isolate, 1.0; glycerol, 0.3	nd	11.04 ± 1.2	17.6 ± 1.6	7.5 ± 0.4	Atarés et al. (2010)
Cinnamon, 0.075	Soy protein isolate, 1.0; glycerol, 0.3	nd	12 ± 1.2	15.2 ± 1.3	7.2 ± 1.6	Atarés et al. (2010)
Cinnamon, 0.1	Soy protein isolate, 1.0; glycerol, 0.3	nd	13.2 ± 2.4	14.1 ± 1	7.5 ± 0.6	Atarés et al. (2010)
Cinnamon, 0.1	Pullulan polysaccharides, 2.0; glycerol, 0.3	nd	1,776*	49.3	2.8	Feng et al. (2020)
Cinnamon, 0.2	Pullulan polysaccharides, 2.0; glycerol, 0.3	nd	1,464*	48.8	2.9	Feng et al. (2020)
Cinnamon, 0.3	Pullulan polysaccharides, 2.0; glycerol, 0.3	nd	1,344*	47.1	3.3	Feng et al. (2020)
Cinnamon, 0.4	Sodium starch octenyl succinate, 4.0; corn oil, 1.6; glycerol, 1.6; sodium alginate, 1.2	nd	3.18*	17.18 ± 0.14	22.58 ± 1.59	Sun et al. (2020)
Cinnamon, 0.8	Sodium starch octenyl succinate, 4.0; corn oil, 1.2; glycerol, 1.6; sodium alginate, 1.2	nd	2.69*	10.80 ± 0.62	35.25 ± 2.21	Sun et al. (2020)
Cinnamon, 1.2	Sodium starch octenyl succinate, 4.0; corn oil, 0.8; glycerol, 1.6; sodium alginate, 1.2	nd	2.47*	10.29 ± 0.32	39.62 ± 2.26	Sun et al. (2020)
Cinnamon, 1.6	Sodium starch octenyl succinate, 4.0; corn oil, 0.4; glycerol, 1.6; sodium alginate, 1.2	nd	1.79*	8.77 ± 0.35	45.22 ± 1.80	Sun et al. (2020)
Cinnamon, 2.0	Sodium starch octenyl succinate, 4.0; glycerol, 1.6; sodium alginate, 1.2	nd	2.22*	8.65 ± 0.21	53.25 ± 3.65	Sun et al. (2020)
Cinnamon, 0.5	Chitosan, 2.0 in acetic acid, 1.0; glycerol, 30.0; Tween 80, 20.0	17.28 ± 0.97	147,024.0*	43.11 ± 6.39	28.05 ± 2.91	Zhang et al. (2019)
Cinnamon, 0.4	Chitosan, 2.0 in acetic acid, 1.0; glycerol, 1.5; Tween 80, 0.0008	21.06 ± 0.65	11.68*	13.35 ± 1.23	16.57 ± 0.77	Ojagh et al. (2010)
Cinnamon, 0.8	Chitosan, 2.0 in acetic acid, 1.0; glycerol, 1.5; Tween 80, 0.0016	16.8 ± 0.85	10.66*	17.43 ± 1.08	11.26 ± 1.39	Ojagh et al. (2010)
Cinnamon, 1.5	Chitosan, 2.0 in acetic acid, 1.0; glycerol, 1.5; Tween 80, 0.003	13.6 ± 1.55	8.76*	24.10 ± 1.47	6.42 ± 0.63	Ojagh et al. (2010)
Cinnamon, 2.0	Chitosan, 2.0 in acetic acid, 1.0; glycerol, 1.5; Tween 80, 0.004	10.4 ± 0.94	8.67*	19.23 ± 2.25	3.58 ± 0.35	Ojagh et al. (2010)

Continue...

Table 2. Continuation...

Essential oil (g·100 g^{-1})	Other compounds (g·100 g^{-1})	Sw (%)	WVP (g·mm·d^{-1}·kPa^{-1}·m^{-2})	TS (Mpa)	EB (%)	Reference
Cinnamon, 1.0	Chitosan, 2.0 in acetic acid, 1.0; glycerol, 0.6; Tween 20, 0.1	39.02 ± 3.17	7.7*	38.7*	12.2*	Peng and Li (2014)
Cinnamon, 0.8	Sugar palm (SP) starch, 10.0; SP cellulose, 0.05; glycerol, 1.5; sorbitol, 1.5; Tween 80, 1.5	nd	nd	4.81	17.2475	Syafiq et al. (2021)
Cinnamon, 1.2	Sugar palm (SP) starch, 10.0; SP cellulose, 0.05; glycerol, 1.5; sorbitol, 1.5; Tween 80, 1.5	nd	nd	4.94	16.350	Syafiq et al. (2021)
Cinnamon, 1.6	Sugar palm (SP) starch, 10.0; SP cellulose, 0.05; glycerol, 1.5; sorbitol, 1.5; Tween 80, 1.5	nd	nd	5.08	15.575	Syafiq et al. (2021)
Cinnamon, 2.0	Sugar palm (SP) starch, 10.0; SP cellulose, 0.05; glycerol, 1.5; sorbitol, 1.5; Tween 80, 1.5	nd	nd	5.3 ± 0.27	13.9 ± 5.57	Syafiq et al. (2021)
Cinnamon, 0.5	Silver carp skin gelatin, 4.0; glycerol, 1.0; Tween 80, 0.5	nd	10.80	17.77 ± 1.93	125.60 ± 2.50	Wu et al. (2017)
Cinnamon, 1.0	Silver carp skin gelatin, 4.0; glycerol, 1.0; Tween 80, 0.5	nd	13.56	12.66 ± 1.47	119.05 ± 1.41	Wu et al. (2017)
Cinnamon, 2.0	Silver carp skin gelatin, 4.0; glycerol, 1.0; Tween 80, 0.5	nd	13.13	8.55 ± 0.39	95.55 ± 2.54	Wu et al. (2017)
Cinnamon, 4.0	Silver carp skin gelatin, 4.0; glycerol, 1.0; Tween 80, 0.5	nd	17.02	5.03 ± 0.32	122.17 ± 0.05	Wu et al. (2017)
Cinnamon, 6.0	Silver carp skin gelatin, 4.0; glycerol, 1.0; Tween 80, 0.5	nd	15.64	4.64 ± 1.19	84.33 ± 5.37	Wu et al. (2017)
Cinnamon, 0.05 / perilla, 0.45	Chitosan, 3.0 in acetic acid, 2.0; collagen, 3.0; glycerol, 0.5; anthocyanidin 0.4	nd	32.12 ± 2.68	7.20*	140.00 ± 8.43	Zhao et al. (2022)
Cinnamon, 0.1 / perilla, 0.9	Chitosan, 3.0 in acetic acid, 2.0; collagen, 3.0; glycerol, 0.5; anthocyanidin 0.4	nd	31.40 ± 3.65	4.56*	140.96 ± 7.65	Zhao et al. (2022)
Cinnamon, 0.15 / perilla, 1.35	Chitosan, 3.0 in acetic acid, 2.0; collagen, 3.0; glycerol, 0.5; anthocyanidin 0.4	nd	19.49 ± 2.22	6.00*	114.29 ± 5.10	Zhao et al. (2022)
Cinnamon, 0.2 / perilla, 1.8	Chitosan, 3.0 in acetic acid, 2.0; collagen, 3.0; glycerol, 0.5; anthocyanidin 0.4	nd	19.46 ± 1.53	7.68*	91.61 ± 5.28	Zhao et al. (2022)
Cinnamon, 0.3 / perilla, 2.7	Chitosan, 3.0 in acetic acid, 2.0; collagen, 3.0; glycerol, 0.5; anthocyanidin 0.4	nd	12.83 ± 0.44	11.76*	92.20 ± 3.80	Zhao et al. (2022)
Cinnamon, 0.5 / lemon, 0.5	Chitosan, 2.0 in acetic acid, 1.0; glycerol, 0.6; Tween 20, 0.1	25.32 ± 2.14	6.5*	48*	8.9*	Peng and Li (2014)
Cinnamon, 0.5 / thyme, 0.5	Chitosan, 2.0 in acetic acid, 1.0; glycerol, 0.6; Tween 20, 0.1	43.66 ± 4.03	7.3*	42*	14.4*	Peng and Li (2014)
Citronella, 0.1	Chitosan, 1.0 in acetic acid, 1.0; Tween 80, 0.001	nd	30.2*	33.00 ± 1.94	14.50 ± 0.50	Shen and Kamdem (2015b)
Citronella, 0.2	Chitosan, 1.0 in acetic acid, 1.0; Tween 80, 0.002	nd	27.6*	29.42 ± 0.47	24.50 ± 0.50	Shen and Kamdem (2015b)
Citronella, 0.3	Chitosan, 1.0 in acetic acid, 1.0; Tween 80, 0.003	nd	24.2*	17.12 ± 2.25	8.25 ± 1.92	Shen and Kamdem (2015b)

Continue...

Table 2. Continuation...

Essential oil (g·100 g-1)	Other compounds (g·100 g-1)	Sw (%)	WVP (g·mm·d-1·kPa-1·m-2)	TS (Mpa)	EB (%)	Reference
Clove, 0.025	Chitosan, 1.0 in acetic acid, 1.0; oleic acid, 1.0	nd	43.72*	6.7 ± 0.4	56.7 ± 1.7	Wang et al. (2021)
Clove, 0.05	Chitosan, 1.0 in acetic acid, 1.0; oleic acid, 1.0	nd	39.92*	6.2 ± 0.8	69.0 ± 2.6	Wang et al. (2021)
Clove, 0.75	Chitosan, 1.0 in acetic acid, 1.0; oleic acid, 1.0	nd	34.73*	6.3 ± 1.3	78.6 ± 3.1	Wang et al. (2021)
Clove, 0.07	Polyhydroxybutyrate, 1.197; poly(ethylene glycol), 0.133	nd	nd	13.76 ± 0.35	3.70 ± 0.49	Silva, I. D. L. et al. (2020)
Clove, 0.14	Polyhydroxybutyrate, 1.134; poly(ethylene glycol), 0.126	nd	nd	12.22 ± 0.32	3.08 ± 0.08	Silva, I. D. L. et al. (2020)
Clove, 0.21	Polyhydroxybutyrate, 1.071; poly(ethylene glycol), 0.119	nd	nd	8.10 ± 1.84	9.77 ± 1.01	Silva, I. D. L. et al. (2020)
Clove, 0.18	Silica nanoparticles, 1.0; poly(L-lactic acid), 1.6; polycaprolactone, 0.4	nd	0.21*	19.40 ± 0.74	26.4 ± 0.57	Lu et al. (2021)
Clove, 0.18	Silica nanoparticles, 2.0; poly(L-lactic acid), 1.6; polycaprolactone, 0.4	nd	0.34*	16.90 ± 0.88	30.6 ± 0.95	Lu et al. (2021)
Clove, 0.18	Silica nanoparticles, 3.0; poly(L-lactic acid), 1.6; polycaprolactone, 0.4	nd	0.51*	11.8 ± 0.16	30.7 ± 1.12	Lu et al. (2021)
Clove, 0.1	Hybrid sorubim protein isolate, 1.5; glycerol, 0.37	30.10 ± 0.01	6.05 ± 1.5	3.92 ± 0.5	23.38 ± 0.7	Silva, R. S. et al. (2020)
Clove, 0.1	Hybrid sorubim protein isolate, 2.5; glycerol, 0.37	25.55 ± 0.01	5.72 ± 1.1	4.04 ± 1.0	14.40 ± 1.7	Silva, R. S. et al. (2020)
Clove, 0.1	Hybrid sorubim protein isolate, 1.5; glycerol, 0.37	44.90 ± 0.04	9.0 ± 1.2	0.55 ± 0.1	44.39 ± 1.9	Silva, R. S. et al. (2020)
Clove, 0.1	Hybrid sorubim protein isolate, 2.5; glycerol, 0.37	37.03 ± 0.04	9.33 ± 1.0	1.76 ± 0.3	23.71 ± 0.2	Silva, R. S. et al. (2020)
Clove, 0.3	Hybrid sorubim protein isolate, 2.0; glycerol, 0.6	31.27 ± 3.59	6.35 ± 1.24	1.14 ± 0.0	16.14 ± 0.8	Silva, R. S. et al. (2020)
Clove, 0.5	Hybrid sorubim protein isolate, 1.5; glycerol, 0.87	29.57 ± 0.02	4.32 ± 1.2	1.27 ± 0.4	16.28 ± 0.7	Silva, R. S. et al. (2020)
Clove, 0.5	Hybrid sorubim protein isolate, 2.5; glycerol, 0.87	22.05 ± 0.04	5.16 ± 1.0	6.7 ± 0.4	10.40 ± 1.0	Silva, R. S. et al. (2020)
Clove, 0.5	Hybrid sorubim protein isolate, 1.5; glycerol, 0.87	33.73 ± 0.05	8.93 ± 1.6	2.00 ± 1.7	27.00 ± 0.3	Silva, R. S. et al. (2020)
Clove, 0.5	Hybrid sorubim protein isolate, 2.5; glycerol, 0.87	30.71 ± 0.03	8.77 ± 1.7	1.49 ± 0.2	17.75 ± 1.0	Silva, R. S. et al. (2020)
Clove, 0.4	Nile tilapia protein isolate, 1.5; glycerol, 0.2; nanoclay, 0.3	65.47 ± 2.16	2.38 ± 0.14	2.21 ± 0.40	0.29 ± 0.20	Scudeler et al. (2020)
Clove, 0.4	Nile tilapia protein isolate, 1.5; glycerol, 0.4; nanoclay, 0.1	53.55 ± 3.06	3.14 ± 0.60	2.25 ± 0.31	1.22 ± 0.05	Scudeler et al. (2020)
Clove, 0.3	Bocaiuva flour, 1.5; glycerol, 0.5	2.6 ± 0.3	6.9 ± 0.4	16.4 ± 0.04	62.2 ± 0.02	da Silva et al. (2020)
Clove, 0.3	Bocaiuva flour, 2.5; glycerol, 0.5	4.1 ± 0.1	6.5 ± 2.4	30.2 ± 0.05	49.3 ± 0.04	da Silva et al. (2020)
Clove, 0.3	Bocaiuva flour, 1.5; glycerol, 0.7	2.6 ± 0.3	5.2 ± 1.2	6.8 ± 0.01	38.8 ± 0.01	da Silva et al. (2020)
Clove, 0.3	Bocaiuva flour, 2.5; glycerol, 0.7	3.5 ± 0.3	7.2 ± 1.3	10.8 ± 0.02	68.5 ± 0.05	da Silva et al. (2020)
Clove, 0.5	Bocaiuva flour, 2.0; glycerol, 0.6	4.3 ± 0.7	8.7 ± 1.7	16.1 ± 0.01	56.9 ± 0.04	da Silva et al. (2020)
Clove, 0.7	Bocaiuva flour, 1.5; glycerol, 0.5	2.7 ± 0.2	6.8 ± 1.1	4.8 ± 0.02	26.0 ± 0.05	da Silva et al. (2020)

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Table 2. Continuation...

Essential oil ($g \cdot 100\ g^{-1}$)	Other compounds ($g \cdot 100\ g^{-1}$)	Sw (%)	WVP ($g \cdot mm \cdot d^{-1} \cdot kPa^{-1} \cdot m^{-2}$)	TS (Mpa)	EB (%)	Reference
Clove, 0.7	Bocaiuva flour, 2.5; glycerol, 0.5	4.9 ± 0.8	3.8 ± 0.3	20.7 ± 0.03	30.4 ± 0.09	da Silva et al. (2020)
Clove, 0.7	Bocaiuva flour, 1.5; glycerol, 0.7	2.8 ± 0.2	7.9 ± 1.5	5.0 ± 0.01	43.8 ± 0.06	da Silva et al. (2020)
Clove, 0.7	Bocaiuva flour, 2.5; glycerol, 0.7	4.4 ± 0.4	9.3 ± 3.2	12.9 ± 0.03	47.1 ± 0.03	da Silva et al. (2020)
Clove, 1.0	Chitosan, 1.0 in acetic acid, 1.0; glycerol, 0.40; halloysite nanotubes, 0.05	29.83 ± 0.56	24.4*	14.5*	24*	Lee et al. (2018)
Clove, 1.0	Chitosan, 1.0 in acetic acid, 1.0; glycerol, 0.40; halloysite nanotubes, 0.1	30.23 ± 0.81	23.5*	18*	25*	Lee et al. (2018)
Clove, 1.0	Chitosan, 1.0 in acetic acid, 1.0; glycerol, 0.40; halloysite nanotubes, 0.15	30.21 ± 0.82	22.7*	21.5*	27*	Lee et al. (2018)
Clove, 1.0	Chitosan, 1.0 in acetic acid, 1.0; glycerol, 0.40; halloysite nanotubes, 0.2	29.91 ± 0.65	22.0*	19*	26*	Lee et al. (2018)
Clove, 1.0	Chitosan, 1.0 in acetic acid, 1.0; glycerol, 0.40; halloysite nanotubes, 0.25	29.77 ± 1.35	21.3*	15.5*	24*	Lee et al. (2018)
Clove, 1.0	Chitosan, 1.0 in acetic acid, 1.0; glycerol, 0.40; halloysite nanotubes, 0.3	29.59 ± 0.51	20.9*	15*	23*	Lee et al. (2018)
Clove ($1\ \mu L \cdot cm^{-2}$)	Hake protein powder, 1.5; glycerol (59 g $100\ g^{-1}$ protein)	10*	3.3*	7.3 ± 2.3	55.7± 31.7	Teixeira et al. (2014)
Clove, 0.4 / Oregano, 0.4	Nile tilapia protein isolate, 1.5; glycerol, 0.2; nanoclay, 0.1	13.40 ± 0.65	2.75 ± 0.74	2.41 ± 0.42	0.48 ± 0.08	Scudeler et al. (2020)
Clove, 0.2 / Oregano, 0.2	Nile tilapia protein isolate, 1.0; glycerol, 0.3; nanoclay, 0.2	60.78 ± 2.12	3.75 ± 0.48	0.65 ± 0.18	0.93 ± 0.24	Scudeler et al. (2020)
Clove, 0.4 / Oregano, 0.4	Nile tilapia protein isolate, 1.5; glycerol, 0.4; nanoclay, 0.3	45.92 ± 3.01	3.19 ± 0.05	1.36 ± 0.41	0.65 ± 0.12	Scudeler et al. (2020)
Eucalyptus, 0.5	Chitosan, 1.5 in acetic acid, 0.7; glycerol 0.225; Tween 80, 0.001	23.94 ± 1.66	2.45*	34.5 ± 0.5	25.24 ± 0.5	Azadbakht et al. (2018)
Eucalyptus, 1.0	Chitosan, 1.5 in acetic acid, 0.7; glycerol 0.225; Tween 80, 0.002	19.63 ± 1.22	4.38*	30.0 ± 0.2	28.03 ± 0.61	Azadbakht et al. (2018)
Eucalyptus, 1.5	Chitosan, 1.5 in acetic acid, 0.7; glycerol 0.225; Tween 80, 0.003	15.88 ± 2.01	5.36*	26.6 ± 0.32	35.74 ± 0.72	Azadbakht et al. (2018)
Fingerroot, 1.5	HPMC, 2.0; montmorillonite, 0.1; beeswax, 0.4; stearic acid, 0.4; glycerol, 0.67	nd	56.69 ± 1.35	5*	7.5*	Klangmuang and Sothornvit (2016)
Garlic (1 μL•cm-2)	Hake protein powder, 1.5; glycerol (59 g 100 g-1 protein)	23*	3.7*	6.6 ± 2.7	53.3 ± 21.1	Teixeira et al. (2014)
Garlic, 1.0 and thyme, 1.0	Zein, 2.0 in ethanol (90% vol.)	2.11 ± 0.07	0.0454*	4.83 ± 0.10	0.80 ± 0.04	Pereira et al. (2019)
Garlic, 1.5 and thyme, 1.5	Zein, 2.0 in ethanol (90% vol.)	0.83 ± 0.04	0.0444*	4.23 ± 0.15	0.76 ± 0.04	Pereira et al. (2019)
Garlic, 2.5 and thyme, 2.5	Zein, 2.0 in ethanol (90% vol.)	0.54 ± 0.03	0.0380*	3.26 ± 0.03	0.42 ± 0.03	Pereira et al. (2019)
Ginger, 0.1	Chitosan, 1.0 in acetic acid, 1.0; glycerol, 0.1; Tween 80, 0.05	nd	nd	31.9 ± 0.33	18.18 ± 0.02	Remya et al. (2016)
Ginger, 0.2	Chitosan, 1.0 in acetic acid, 1.0; glycerol, 0.1; Tween 80, 0.05	nd	nd	31.8 ± 0.52	18.19 ± 0.05	Remya et al. (2016)

Continue...

Table 2. Continuation...

Essential oil (g·100 g^{-1})	Other compounds (g·100 g^{-1})	Sw (%)	WVP (g·mm·d^{-1}·kPa^{-1}·m^{-2})	TS (Mpa)	EB (%)	Reference
Ginger, 0.3	Chitosan, 1.0 in acetic acid, 1.0; glycerol, 0.1; Tween 80, 0.05	nd	nd	30.9 ± 0.35	18.20 ± 0.02	Remya et al. (2016)
Ginger, 0.025	Soy protein isolate, 1.0; glycerol, 0.3	nd	6 ± 3	13.51 ± 0.67	1.7 ± 0.6	Atarés et al. (2010)
Ginger, 0.05	Soy protein isolate, 1.0; glycerol, 0.3	nd	4 ± 2	14.02 ± 0.94	1.0 ± 0.6	Atarés et al. (2010)
Ginger, 0.075	Soy protein isolate, 1.0; glycerol, 0.3	nd	8 ± 4	16.08 ± 1.2	3 ± 2	Atarés et al. (2010)
Ginger, 0.1	Soy protein isolate, 1.0; glycerol, 0.3	nd	8 ± 5	16.32 ± 1.92	3 ± 3	Atarés et al. (2010)
Ginger, 1.0	Chitosan, 1.5 in acetic acid, 1.0; glycerol, 0.45; Tween, 0.002	15 ± 0	nd	18 ± 3	35 ± 10	Souza et al. (2017)
Ginger, 1.5	HPMC, 2.0; montmorillonite, 0.1; beeswax, 0.4; stearic acid, 0.4; glycerol, 0.67	nd	65.68 ± 4.57	9.5*	66*	Klangmuang and Sothornvit (2016)
Lavander, 0.5	Chitosan, 1.5; Tween 80, 0.1	18.30 ± 0.82	11.40*	17.54 ± 0.98	17.18 ± 0.72	Zhang et al. (2013)
Lavander, 1.0	Chitosan, 1.5; Tween 80, 0.1	16.05 ± 0.66	10.54*	28.57 ± 0.56	18.23 ± 0.02	Zhang et al. (2013)
Lavander, 1.5	Chitosan, 1.5; Tween 80, 0.1	14.02 ± 0.57	9.24*	31.12 ± 0.63	17.83 ± 0.95	Zhang et al. (2013)
Lemon, 1.0	Chitosan, 2.0 in acetic acid, 1.0; glycerol, 0.6; Tween 20, 0.1	28.95 ± 1.63	7.7*	46*	8.9*	Peng and Li (2014)
Lemon, 0.5 / thyme, 0.5	Chitosan, 2.0 in acetic acid, 1.0; glycerol, 0.6; Tween 20, 0.1	34.88 ± 3.05	7.0*	44.7*	10.6*	Peng and Li (2014)
Lemongrass, 0.15	Unicorn leatherjacket skin gelatin, 3.0; glycerol, 0.6; Tween 20, 0.0225	93.54 ± 0.66	10.5 ± 0.3	43.82 ± 6.56	3.48 ± 0.92	Ahmad et al. (2012)
Lemongrass, 0.3	Unicorn leatherjacket skin gelatin, 3.0; glycerol, 0.45; Tween 20, 0.045	92.3 ± 0.65	8.9 ± 0.6	39.05 ± 5.96	4.13 ± 2.14	Ahmad et al. (2012)
Lemongrass, 0.45	Unicorn leatherjacket skin gelatin, 3.0; glycerol, 0.3; Tween 20, 0.0675	92.04 ± 0.57	8.6 ± 0.5	34.07 ± 3.61	4.80 ± 1.04	Ahmad et al. (2012)
Lemongrass, 0.6	Unicorn leatherjacket skin gelatin, 3.0; glycerol, 0.15; Tween 20, 0.09	89.81 ± 0.5	9.7 ± 0.7	25.84 ± 2.36	5.90 ± 1.66	Ahmad et al. (2012)
Lemongrass, 0.75	Unicorn leatherjacket skin gelatin, 3.0; Tween 20, 0.1125	89.16 ± 0.65	9.2 ± 0.4	21.21 ± 3.36	5.66 ± 2.34	Ahmad et al. (2012)
Lemongrass, 0.015	Chitosan, 1.5 in acetic acid, 1.5; glycerol, 0.5; Tween 20, 0.5	7.39 ± 0.92	2,039.0*	14.61 ± 1.78	37.47 ± 4.06	Lyn and Hanani (2020)
Lemongrass, 0.045	Chitosan, 1.5 in acetic acid, 1.5; glycerol, 0.5; Tween 20, 0.5	7.02 ± 0.01	1,978.6*	11.20 ± 1.68	38.22 ± 2.75	Lyn and Hanani (2020)
Lemongrass, 0.075	Chitosan, 1.5 in acetic acid, 1.5; glycerol, 0.5; Tween 20, 0.5	6.70 ± 0.56	1,944.0*	9.10 ± 0.71	55.95 ± 2.62	Lyn and Hanani (2020)
Lemongrass, 0.105	Chitosan, 1.5 in acetic acid, 1.5; glycerol, 0.5; Tween 20, 0.5	5.97 ± 1.31	1,926.7*	8.48 ± 1.12	56.24 ± 4.07	Lyn and Hanani (2020)
Lemongrass, 0.135	Chitosan, 1.5 in acetic acid, 1.5; glycerol, 0.5; Tween 20, 0.5	5.22 ± 0.43	1,900.8*	7.93 ± 1.19	65.34 ± 3.82	Lyn and Hanani (2020)
Lemongrass, 1.0	Sodium alginate, 3.0; glycerol, 2.0; Tween 80, 3.0	nd	18.32*	6.1*	32 ± 9	Acevedo-Fani et al. (2015)
Orange peel, 0.25	Tonguefish skin gelatin, 3.0; chitosan, 2.0; glycerol, 2.5; acetic acid, 1.0	28.25 ± 1.53	0.96*	20.43 ± 0.82	2.73 ± 0.04	Li et al. (2021)
Orange peel, 0.5	Tonguefish skin gelatin, 3.0; chitosan, 2.0; glycerol, 2.5; acetic acid, 1.0	25.55 ± 0.62	0.74*	19.35 ± 0.31	3.55 ± 0.07	Li et al. (2021)

Continue...

Table 2. Continuation...

Essential oil (g·100 g⁻¹)	Other compounds (g·100 g⁻¹)	Sw (%)	WVP (g·mm·d⁻¹·kPa⁻¹·m⁻²)	TS (Mpa)	EB (%)	Reference
Orange peel, 1.0	Tonguefish skin gelatin, 3.0; chitosan, 2.0; glycerol, 2.5; acetic acid, 1.0	23.45 ± 0.70	1.08*	17.80 ± 0.91	4.23 ± 0.23	Li et al. (2021)
Oregano, 0.4	Nile tilapia protein isolate, 1.5; glycerol, 0.2; nanoclay, 0.3	67.49 ± 4.25	2.98 ± 0.87	2.54 ± 0.32	0.30 ± 0.10	Scudeler et al. (2020)
Oregano, 0.4	Nile tilapia protein isolate, 1.5; glycerol, 0.4; nanoclay, 0.1	30.62 ± 2.39	2.56 ± 0.46	1.17 ± 0.46	1.95 ± 0.01	Scudeler et al. (2020)
Oregano, 0.5	Sodium alginate, 1.5; glycerol, 0.3645	nd	328.3*	55.5 ± 5.7	3.0 ± 0.08	Benavides et al. (2012)
Oregano, 1.0	Sodium alginate, 1.5; glycerol, 0.3645	nd	328.3*	46.5 ± 5.4	2.8 ± 0.06	Benavides et al. (2012)
Oregano, 1.5	Sodium alginate, 1.5; glycerol, 0.3645	nd	259.2*	31.1 ± 6.0	2.7 ± 0.11	Benavides et al. (2012)
Oregano (1 µL·cm⁻²)	Hake protein powder, 1.5; glycerol (59 g 100 g⁻¹ protein)	10*	6.7*	6.4 ± 4.0	83.2 ± 50.3	Teixeira et al. (2014)
Perilla, 0.2	Chitosan, 2.0 in 0.5 acetic acid; glycerol, nd	37.993 ± 4.162	5.352*	11.760 ± 0.920	13.267 ± 2.127	Zhang et al. (2018)
Perilla, 0.6	Chitosan, 2.0 in 0.5 acetic acid; glycerol, nd	27.437 ± 2.778	5.112*	12.300 ± 0.915	12.466 ± 5.047	Zhang et al. (2018)
Perilla, 1.0	Chitosan, 2.0 in 0.5 acetic acid; glycerol, nd	21.996 ± 4.366	5.520*	12.477 ± 0.208	9.365 ± 1.434	Zhang et al. (2018)
Plai, 1.5	HPMC, 2.0; montmorillonite, 0.1; beeswax, 0.4; stearic acid, 0.4; glycerol, 0.67	nd	77.73 ± 6.93	11.5*	52*	Klangmuang and Sothornvit (2016)
Rosemary, 0.5	Chitosan, 2.0 in acetic acid, 1.0; Tween 80, 0.2	15.5*	6.9*	68.51 ± 12.22	4.97 ± 0.68	Abdollahi et al. (2012)
Rosemary, 1.0	Chitosan, 2.0 in acetic acid, 1.0; Tween 80, 0.2	13.5*	6.8*	68.90 ± 13.68	5.07 ± 0.79	Abdollahi et al. (2012)
Rosemary, 1.5	Chitosan, 2.0 in acetic acid, 1.0; Tween 80, 0.2	13*	5.9*	65.46 ± 4.63	4.61 ± 0.81	Abdollahi et al. (2012)
Rosemary, 1.0	Chitosan, 1.5 in acetic acid, 1.0; glycerol, 0.45; Tween, 0.002	20 ± 1	nd	28 ± 4	35 ± 5	Souza et al. (2017)
Sage, 1.0	Chitosan, 1.5 in acetic acid, 1.0; glycerol, 0.45; Tween, 0.002	19 ± 0	nd	31 ± 3	35 ± 5	Souza et al. (2017)
Sage, 1.0	Sodium alginate, 3.0; glycerol, 2.0; Tween 80, 3.0	nd	16.42*	4.8*	78 ± 5	Acevedo-Fani et al. (2015)
Shirazi thyme, 0.5	Chitosan, 2.0 in acetic acid, 1.0; glycerol, 1.0	nd	nd	6 ± 0.4	19 ± 0.6	Moradi et al. (2012)
Shirazi thyme, 1.0	Chitosan, 2.0 in acetic acid, 1.0; glycerol, 1.0	nd	nd	3 ± 0.3	10 ± 10	Moradi et al. (2012)
Shirazi thyme, 0.5	Chitosan, 2.0 in acetic acid, 1.0; glycerol, 1.0; grape seed extract, 1.0	nd	nd	23 ± 0.7	17 ± 50	Moradi et al. (2012)
Shirazi thyme, 1.0	Chitosan, 2.0 in acetic acid, 1.0; glycerol, 1.0; grape seed extract, 1.0	nd	nd	15 ± 0.6	39 ± 30	Moradi et al. (2012)
Tea tree, 0.5	HPMC, 5.0; Tween 85, 0.1	nd	64.8*	55 ± 10	0.09 ± 0.04	Sánchez-González et al. (2009)
Tea tree, 1.0	HPMC, 5.0; Tween 85, 0.1	nd	57.0*	52 ± 9	0.11 ± 0.05	Sánchez-González et al. (2009)

Continue...

Table 2. Continuation...

Essential oil (g·100 g⁻¹)	Other compounds (g·100 g⁻¹)	Sw (%)	WVP (g·mm·d⁻¹·kPa⁻¹·m⁻²)	TS (Mpa)	EB (%)	Reference
Tea tree, 2.0	HPMC, 5.0; Tween 85, 0.1	nd	45.8*	42 ± 2	0.11 ± 0.05	Sánchez-González et al. (2009)
Tea tree, 0.5	Chitosan, 1.0 in malic acid, 2.0; lecithin, 0.1	19.41 ± 0.55	3.8 ± 0.4	3.51 ± 0.72	150.55 ± 25.10	Cazón et al. (2021)
Tea tree, 1.0	Chitosan, 1.0 in malic acid, 2.0; lecithin, 0.1	19.26 ± 0.82	3.7 ± 0.2	1.54 ± 0.30	317.33 ± 22.84	Cazón et al. (2021)
Tea tree, 0.5	Chitosan, 1.0 in lactic acid, 2.0; lecithin, 0.1	59.37 ± 0.90	4.2 ± 1.0	4.40 ± 1.11	25.54 ± 7.30	Cazón et al. (2021)
Tea tree, 1.0	Chitosan, 1.0 in lactic acid, 2.0; lecithin, 0.1	58.68 ± 2.28	4.2 ± 0.0	4.09 ± 0.61	33.10 ± 3.08	Cazón et al. (2021)
Tea tree, 1.0	Chitosan, 1.5 in acetic acid, 1.0; glycerol, 0.45; Tween, 0.002	19 ± 0	nd	24 ± 2	38 ± 7	Souza et al. (2017)
Thyme, 1.0	Chitosan, 1.5 in acetic acid, 1.0; glycerol, 0.45; Tween, 0.002	20 ± 1	nd	31 ± 3	38 ± 2	Souza et al. (2017)
Thyme, 0.2	Chitosan, 2.0 in acetic acid, 2.0	nd	38.22 ± 3.12	69.8*	3.6 ± 0.25	Altiok et al. (2010)
Thyme, 0.4	Chitosan, 2.0 in acetic acid, 2.0	nd	41.91 ± 2.83	77.4*	3.6 ± 0.22	Altiok et al. (2010)
Thyme, 0.6	Chitosan, 2.0 in acetic acid, 2.0	nd	31.05 ± 1.95	89.6*	3.2 ± 0.24	Altiok et al. (2010)
Thyme, 0.8	Chitosan, 2.0 in acetic acid, 2.0	nd	34.37 ± 1.51	87.3*	2.7 ± 0.25	Altiok et al. (2010)
Thyme, 1.0	Chitosan, 2.0 in acetic acid, 2.0	nd	34.57 ± 4.29	85.9*	1.9 ± 0.20	Altiok et al. (2010)
Thyme, 1.2	Chitosan, 2.0 in acetic acid, 2.0	nd	32.94 ± 3.32	87.2*	1.8 ± 0.22	Altiok et al. (2010)
Thyme, 1.0	Chitosan, 2.0 in acetic acid, 1.0; glycerol, 0.6; Tween 20, 0.1	42.96 ± 1.03	7.9*	36.7*	13.9*	Peng and Li (2014)
Thyme, 1.0	Sodium alginate, 3.0; glycerol, 2.0; Tween 80, 3.0	nd	18.84*	5.0*	41 ± 12	Acevedo-Fani et al. (2015)
Tung, 0.045	Sugar beet lignocellulose, 0.9; glycerol, 0.1; Span 80, 0.01	nd	22.5 ± 0.9	45.7 ± 6.9	7.7 ± 0.6	Shen and Kamdem (2015a)
Tung, 0.09	Sugar beet lignocellulose, 0.9; glycerol, 0.1; Span 80, 0.01	nd	20.7 ± 0.9	34.3 ± 3.0	3.2 ± 0.5	Shen and Kamdem (2015a)
Tung, 0.135	Sugar beet lignocellulose, 0.9; glycerol, 0.1; Span 80, 0.01	nd	17.3 ± 0.9	32.8 ± 1.8	2.4 ± 0.6	Shen and Kamdem (2015a)
Turmeric, 1.0	Sodium alginate, 1.5; Tween 80, 0.25	nd	164.2	14.18 ± 2.31	5.28 ± 1.81	Phal et al. (2020)
Turmeric, 2.0	Sodium alginate, 1.5; Tween 80, 0.5	nd	198.7	10.22 ± 1.06	10.73 ± 3.49	Phal et al. (2020)
Turmeric, 3.0	Sodium alginate, 1.5; Tween 80, 0.75	nd	259.2	7.74 ± 1.38	14.47 ± 6.76	Phal et al. (2020)
Turmeric (15 μL·cm⁻²)	Chitosan, 2.0 in acetic acid, 1.5; glycerol, 0.3; Tween 80, 1.5 μL·cm⁻²	13.11 ± 2.24	43.88*	32.92 ± 1.81	9.64 ± 1.22	Li et al. (2019)
Wormwood, 1.0	Chitosan, 2.0 in acetic acid, 1.0; glycerol, 0.6; Tween 80, 0.002	90.38 ± 1.27	nd	2.19 ± 0.20	65.20 ± 4.64	Moalla et al. (2021)

SW: water solubility; WVP: water vapor permeability; TS: tensile strength; EB: elongation at break; HPMC: hydroxypropyl methylcellulose; *data obtained from graph/unit conversion; nd: not determined.

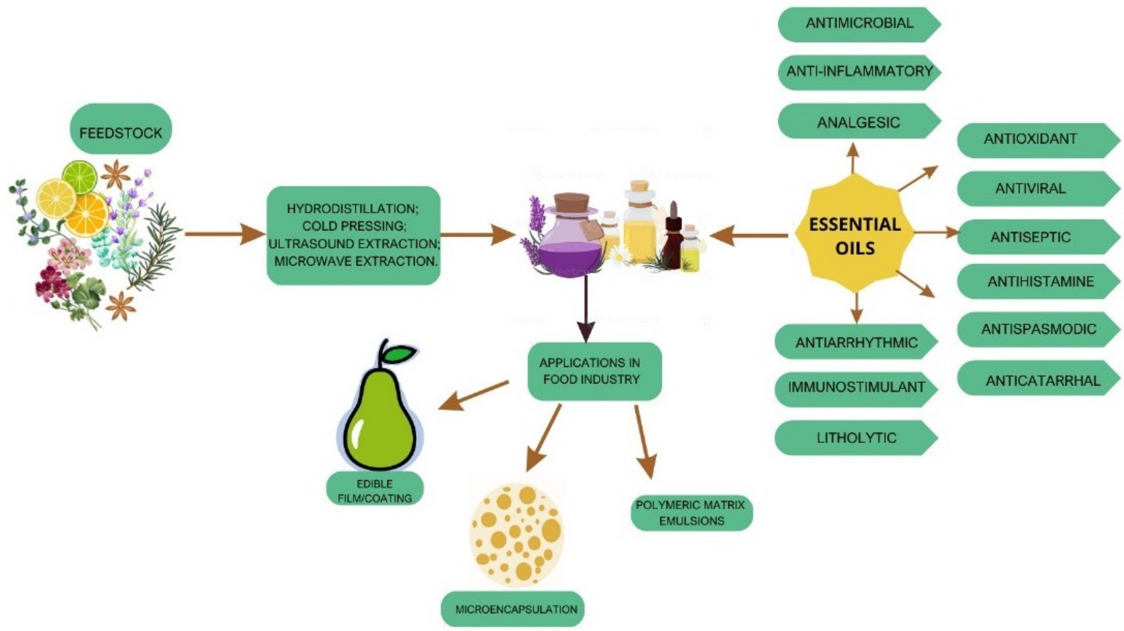

Figure 1. The role of essential oils in food packaging films, coatings and nanoencapsulated materials.

Films containing essential oils

Clove (*Eugenia caryophyllata*) EO has the volatile aromatic oil eugenol as its main component, which has antibacterial, antifungal, antioxidant, insecticidal, and antiviral properties (Silva, I. D. L. et al. 2020, Wang et al. 2020). The presence of eugenol also increases the anti-inflammatory and the antioxidant properties of films and coating for, e.g., apples, strawberries, and ground beef (Santana et al. 2021).

Clove EO was incorporated with polyethylene glycol to polyhydroxybutyrate films, and the addition of 15% w/w changed the chemical structure of the material, resulting in less energy during film processing and more flexible films (Silva, I. D. L. et al. 2020). Clove EO was utilized in the formulation of cassava starch-based films in combination with montmorillonite clay and glycerol. The effect of the components and their concentrations on the solubility, color, water vapor permeability, and opacity of the films was investigated, and the results obtained with the highest concentration of clove EO showed higher solubility, water vapor permeability, and luminosity (Chevalier et al. 2020).

Clove EO, cellulosic nanocrystals obtained from the Kudzu plant (*Pueraria montana*), and corn starch were utilized to produce films for red grape packaging. Results showed red grapes with extended physical and chemical stabilities, due to the maintenance of weight and firmness during storage (Bangar et al. 2022). Clove EO was also utilized in the development of films based on bocaiuva (*Acromonia aculeata*) flour, contributing to the good opacity, easy handling, and homogeneity of the films, which are desirable characteristics for packaging materials (da Silva et al. 2020).

The development of poly(lactic acid) composite films containing nanoparticles of mesoporous silica loaded with clove EO was reported elsewhere, and the compatibility of mesoporous silica loaded with clove EO was analyzed. It was concluded that the loaded nanoparticles inhibited *Staphylococcus aureus* and *Escherichia coli* strains (Lu et al. 2021). The incorporation of clove EO and nisin to chitosan-based films improved the shelf life of chilled pork burgers. The combination of chitosan, nisin, and clove EO was responsible to extend the hamburger's shelf life about twice as compared to the control treatment (Venkatachalam and Lekjing 2020).

Results from a study comparing clove and rosemary (*Salvia rosmarinus*) EOs indicated that clove EO had the highest antifungal activity, increasing the shelf life of whole grain breads when compared to the rosemary EO. However, it was reported that the rosemary EO had greater activity against bacterial strains (Santos et al. 2021).

Oregano (*Origanum vulgare*) EO has being widely used in the production of films by the casting and extrusion technique. The concentration of oregano EO used in the formulation of the films has been quite variable, depending on the type and concentration of biopolymers and plasticizer, which influences the antimicrobial and antioxidant activity by increasing shelf life, without altering sensory characteristic and functional properties of the films. The oregano EO also acts as a plasticizer, reducing hardness and increasing the elongation of the films (Paulo et al. 2021).

Rosemary and oregano EOs were included in the formulation of edible films prepared from gelatin and chitosan, which were evaluated for their mechanical properties and morphology. The films presented antimicrobial activity against the microorganisms *E. coli* and *S. aureus* and antioxidant potential. However, the highest antimicrobial and antioxidant activities were obtained with the films included of oregano EO, which also resulted in an increased perforation resistance (Galindo et al. 2019).

Composite films based on fish skin gelatin, chitosan, and orange (*Citrus* × *sinensis*) peel EO showed slightly lower degradation temperature and weight loss compared to the control film (without orange peel EO). The incorporation of EO orange peel (0.25–1.0%, $v \cdot v^{-1}$) into the films reduced the values of tensile strength, modulus of elasticity, water solubility, moisture content, and water vapor permeability. However, the insertion of orange peel EO raised elongation at break, contact angle and opacity. These characteristics on the films added of orange peel EO had improved their antioxidative and antibacterial activities and flexibility compared to the control film without orange peel EO (Li et al. 2021).

Clove, cinnamon (*Cinnamomum verum*), and orange EOs were utilized in the preparation of poly(lactic acid) films and evaluated as antimicrobial agents in juices, milks, and teas. Among the three EOs studied, orange EO showed no inhibition against *S. aureus* bacteria. In general, cinnamon and clove EOs showed the greatest potential inhibitors against the three *S. aureus* strains used, but clove EO was identified as the most efficient antimicrobial agent (Lima et al. 2021).

Cinnamon EO was emulsified by octenylsuccinate anhydride modified starch on a pullulan solution to obtain pullulan-based films. The cinnamon EO decreased tensile strength, water content, and water vapor permeability, while increasing elongation at break. The growth of *S. aureus* and *E. coli* was inhibited by 60 and 45%, respectively (Feng et al. 2020).

Cinnamon EO was incorporated into starch nanocellulose films, positively affecting the antibacterial, physical, and mechanical properties of the films aimed for food packaging applications (Syafiq et al. 2021). Results from films prepared using cinnamon as antimicrobial agent, glycerol as plasticizer, and Tween 80 as surfactant in a sodium alginate / carboxymethylcellulose matrix indicated that the incorporation of cinnamon EO increased the thickness, water vapor permeability, oxygen permeability, and elongation at break of the films and significantly reduced the moisture content and tensile strength, exhibiting excellent antimicrobial activity against *E. coli* and *S. aureus*. These films showed good results when applied as coatings to preserve bananas (Han et al. 2018).

The incorporation of cinnamon EO and corn oil to sodium starch octenylsuccinate was evaluated for the manufacture of biodegradable films. The combination of cinnamon EO and corn oil revealed films that, despite presenting decreased tensile strength, showed increased elongation, water vapor permeability, and oxygen permeability, beyond activity against the bacteria *E. coli*, *S. aureus*, and *Bacillus subtilis* (Sun et al. 2020).

Cinnamon EO nanoemulsions were included in the formulation of pullulan-based films. The results showed lower permeability to water vapor and greater elongation, due to the hydrophobic and plasticizing effects of cinnamon EO. Although the losses of cinnamon EO during drying and storage, the use of this EO showed significant antibacterial activity (Chu et al. 2020). Cinnamon EO and cellulose nanofibers were incorporated to seaweed biopolymers, which significantly improved the morphology, and the mechanical and hydrophobic properties of the films. The films also exhibited good inhibition potential against *S. aureus* and *E. coli* bacteria (Oyekanmi et al. 2021).

On the other hand, clove, and oregano EOs did not show antimicrobial activity when incorporated to the polymer matrix of Nile tilapia (*Oreochromis niloticus*) protein isolate-based films, indicating that, despite the recognized antimicrobial activity of these compounds, changes in their own structure may during the formation of the polymer matrix structure of the films, reflecting in a loss of this capacity (Scudeler et al. 2020). In another work, the incorporation of clove EO into hybrid surubim (*Pseudoplatystoma reticulatum* × *Pseudoplatystoma corruscans*) protein-based films did not show good antimicrobial inhibition conditions, because the percentage of clove EO was considerably low (Silva, R. S. et al. 2020).

Ginger (*Zingiber officinale*) EO was added to fish sarcoplasmic protein and chitosan-based films to evaluate its effect on the physical, mechanical, antioxidant, and thermal properties of the films. Results showed that light transmittance, elongation, water vapor permeability, and water solubility showed positive results due to the addition of ginger EO to the other compounds in the film, and that the antioxidant and antimicrobial activities of the films were concentration dependent. The application of these films as packages showed significant results in the extending the shelf life of dourado (*Salminus maxillosus*) fish fillets (Cai, L. et al. 2020).

Garlic (*Allium sativum*) and thyme (*Thymus vulgaris*) EOs were utilized to produce zein-based films, which presented inhibitory activity against all bacteria tested and effectiveness as plasticizers, lower solubility, and water absorption (Pereira et al. 2019). However, garlic EO has its application limited due to its intense odor. In this sense, garlic EO is recommended to be utilized encapsulated (Emadzadeh et al. 2021).

Black pepper (*Piper nigrum* L.) EO was loaded in a nanoemulsion together with Cloisite Na+ to reinforce the properties of gelatin films, promoting an increase in the thermal stability and in the porosity of the gelatin matrix. Thus, it presents potential for application in food packaging (Saranti et al. 2021).

Shiso (or perilla) (*Perilla frutescens*) EO was utilized as an additive in the manufacture of chitosan and nisin-based films to extend the shelf life of strawberries. The use of shiso EO in the films showed good antioxidant and antibacterial activity against *S. aureus*, *E. coli*, *Salmonella enteritidis*, and *Pseudomonas tolaasii*. The data obtained showed significant mechanical and optical properties. Its application on strawberries delayed their decomposition during storage (Wang et al. 2021).

The combination of cinnamon EO and perilla EO was evaluated as antimicrobial agents in the production of edible films from Pickering emulsions, using collagen as emulsifier. The edible film showed increased mechanical properties, water vapor permeability, thermal stability, hydrophobicity, and antioxidant activity of the film when incorporated of both cinnamon and perilla EOs. The films were utilized for the conservation of cooled fish fillet, demonstrating effectiveness in controlling quality changes in fish fillets during eight days under refrigerated storage (Zhao et al. 2022).

Turmeric EO and anthocyanin extracts were added to a chitosan matrix reinforced with chitin alpha-nanocrystals to develop smart pH-sensitive films. The addition of turmeric EO in this matrix improved the mechanical strength and the hydrophobicity properties and reduced the water solubility and the moisture content. Interestingly, the films also showed near-total blockage against ultraviolet and visible light at wavelengths below 550 nm, indicating a potential smart application for food packaging (Fernández-Marín et al. 2022).

Tea tree (*Melaleuca alternifolia*) EO was included in the formulation of chitosan-based films with two different solvents (lactic acid and malic acid) and related to the obtaining of easily removable films with good ultraviolet barrier property, higher antioxidant activity, and elongation at break when associated with malic acid (Cazón et al. 2021).

Coatings containing essential oils

Peppermint (*Mentha* × *piperita*) EO was incorporated into chitosan-based coatings to inhibit fungi growth during papaya (*Carica papaya* L.) storage in refrigerators. Peppermint EO also decreased opacity and solubility properties, in addition to improving the light barrier and protection against oxidative processes (Braga et al. 2020).

Thyme and oregano EOs incorporated into an alginate-based coating preserved the microbiological quality of minimally processed papaya. On the other hand, the treatment that contained only alginate did not demonstrate efficacy against microbial activity (Tabassum and Khan 2020).

The use of cinnamon and oregano EO incorporated in sodium alginate, potato starch, chitosan, and zein was effective in delaying the germination of russet potato and purple sweet potato at room temperature (Emragi et al. 2022). The combination of pectin with lemon EO and reuterin was efficient in preserving strawberries against fungal spoilage during storage at refrigerated conditions (Hernández-Carrillo et al. 2021).

The coating obtained by starch added of citronella EO to preserve post-harvest papaya revealed that citronella EO, despite preventing the growth of filamentous fungi and yeasts, did not act as a good antimicrobial agent. Moreover, the mass loss was considerable (Aquino et al. 2021a). It is worth mentioning that citronella EO is not indicated to human consumption (Table 1).

Cassava starch-based coatings added of glycerol and clove EO were applied to minimally processed “Formosa” papaya, which efficiently maintained the sensory quality and delayed the microbial growth, increasing the shelf life of the product (Holsbach et al. 2019).

Eucalyptus (*Eucalyptus staigeriana*), rosemary-pepper (*Lippia sidoides*) and cataia (Pimenta *pseudocaryophyllus*) EOs were associated to a carboxymethylcellulose coating for papaya and had evaluated their activity against the fungus *Colletotrichum gloeosporioides*. Rosemary-pepper EO was the best antifungal agent according to the *in-vitro* tests, with the predominance of thymol in its composition, while the *in-vivo* tests showed that rosemary-pepper EO contributed to reduction of the anthracnose disease, delaying the rotting of the fruit, and increasing the shelf life from five to nine days (Zillo et al. 2018).

Basil (*Ocimum basilicum*) EO together with glycerol and starch was analyzed as coatings on cherry tomato (*Solanum lycopersicum* var. cerasiforme). The addition of basil EO proved to be efficient to inhibit the growth of mesophilic aerobic microorganisms and filamentous fungi, also improving the physical characteristics of the fruits (Aquino et al. 2021b).

Lemon (*Citrus limon*) EO was evaluated as anti-browning and antioxidant additive in an aloe (*Aloe vera*) based-gel coating to improve the postharvest quality of Fuji apples (*Malus pumila* var. Red Delicious × Ralls Janet). The results showed better characteristics in terms of soluble solids content, titratable acidity, and pH, in relation to the reduction in senescence processes. The analysis of minerals, vitamin, and other essential elements showed that the treatments did not change the intrinsic characteristics of the treated samples, maintaining them constant during the storage (Farina et al. 2020).

Star anise (*Illicium verum*) EO, polylysine, and nisin were evaluated as coating on meat. The shelf life was extended from eight to 16 days due to inhibition of bacterial growth during storage. The results of the sensorial analysis suggested good retention of color, odor, and global acceptance of the samples by the application of the star anise EO (Liu et al. 2020).

Cinnamon EO was included in the formulation of chitosan-based coatings applied to minimally processed pineapple (*Ananas comosus*). The combination of these two compounds showed satisfactory delay in the appearance of yeasts and molds, and reduced loss of weight and consistency, extending the shelf life of the fruits (Basaglia et al. 2021).

Thyme EO was tested together with chitosan emulsions in the production of coatings for Karish cheese, showing antimicrobial activity for four weeks by decreasing the concentration of aerobic and psychrotrophic bacteria, yeasts, and molds (Al-Moghazy et al. 2021).

Oregano EO was utilized in the production of chitosan-based coatings for the conservation of refrigerated sururu (*Mytella charruana*), presenting antimicrobial activity, minimizing protein deterioration, and increasing shelf life (Oliveira et al. 2019).

Nanoencapsulated materials containing essential oils (emulsions for films and coatings)

The advancement of nanotechnology has trigger out the development of strategies for the nanoencapsulation of EOs from nanoemulsions. It has become a promising alternative, as the low solubility in the aqueous phase, the high volatility, and the low long-term stability are limiting factors for their use as natural preservatives in replacement of the chemical preservatives traditionally used (Lenetha 2022).

Hydroxypropyl methylcellulose-based films incorporated with oregano EO nanoemulsions showed higher elongation at break in relation to the control films, but lower tensile strength and Young’s modulus. The films showed higher opacity and lower ultraviolet and water vapor transmittance, indicating that the incorporation of oregano EO resulted in improved barrier properties. Regarding their antibacterial activity, the composite films were effective against all bacterial strains tested, particularly against *Salmonella typhimurium*. The antioxidant analysis showed values higher than the values of the control films (Lee et al. 2019).

Nanoemulsions of cardamom (*Elettaria cardamomum*), Chinese pepper (*Litsea cubeba*), cinnamon, and Tahiti lemon (*Citrus aurantifolia*) EOs were developed as partial substitutes of chemical preservatives for the control of *Clostridium sporogenes* in mortadella. The EOs showed antimicrobial activity both in isolated and nanoemulsified forms. In addition, they were able to decrease lipid oxidation in relation to the control, acting as good antioxidant agents (Pinelli et al. 2019, 2021).

Nanoencapsulated ajowan (*Trachyspermum ammi*) EO in edible alginate-based coatings was very effective in controlling the growth of the food-borne pathogen *Listeria monocytogenes* in turkey (*Meleagris gallopavo domesticus*) fillets, especially in the nanoencapsulation form (Kazemeini et al. 2021). The bacterial count in the uncoated samples increased from 6.35 to

8.71 log CFU/g on day 12, while it decreased in all other treatments. The lowest number of counted bacteria was observed for the samples coated with 3% alginate containing 1% ajowan EO as nanoemulsion (5.13 log CFU/g), which represented a reduction rate averaging 1.99 logs in the counts of L. monocytogenes compared to the control treatment (uncoated sample).

The electrospraying method was utilized for the development of an oregano EO loaded-chitosan nanoparticle delivery systems with antifungal efficacy against *Alternaria alternata* (Yilmaz et al. 2019). This technique has facilitated the applicability of the EOs as antimicrobials to control their release with prolonged preservative effect in cosmetic, pharmaceutical, and food applications for adjustable dosage forms.

The efficacy of chitosan, alginate-chitosan, chitosan-guar gum, xanthan-chitosan, and pectin-chitosan for the synthesis of pH-responsive biopolymeric nanocapsules for rosemary, clove, and thyme EOs was evaluated. All EOs studied showed low inhibitory activity against *Saccharomyces cerevisiae*, but they presented antibacterial properties against *S. aureus* and *E. coli* when nanoencapsulated in chitosan-guar gum (Skalickova et al. 2020).

Cinnamon, rosemary, and oregano EOs nanoencapsulated in oil-water nanoemulsions prepared by high-frequency ultrasound were applied to fresh celery inoculated with *E. coli* and *L. monocytogenes*. The nanoemulsions of OEs compared to non-encapsulated OEs were more effective against the bacteria, requiring less than 50% of the OEs to reduce the bacterial population. In addition, the oregano EO showed greater inhibition against these bacteria among the EOs evaluated (Dávila-Rodríguez et al. 2019).

Cinnamon EO nanoencapsulated in hydroxypropyl-β-cyclodextrin adjunct nanoemulsions was evaluated against *E. coli* and *S. aureus*, and it was demonstrated that the addition of hydroxypropyl-β-cyclodextrin contributed to the increase in the antimicrobial activity of cinnamon EO nanoemulsions (Hou et al. 2021).

A nanoemulsion of fennel (*Foeniculum vulgare*) EO, cinnamic aldehyde, glycerin, and chitosan utilized to coat pork patties had an inhibitory effect on *E. coli* and *S. aureus*, maintaining the moisture, flavor, and texture of the samples, and extending the shelf life from six to ten days (Sun et al. 2021).

Tea tree EO was nanoencapsulated in gliadin particles with gum arabic, controlling *Salmonella typhimurium* contamination on the surface of meat products for five days, beyond improving tensile strength and elongation at break of nanofibers (Cai et al. 2021).

Garlic EO and nanoencapsulated garlic EO added to chitosan and whey protein were utilized in vacuum-packed refrigerated sausages for 50 days, retarding the growth of the main spoilage bacterial groups with the maintenance of the lipid stability (Esmaeili et al. 2020).

Ylang ylang (*Cananga odorata*) EO and ylang ylang nanoencapsulated in chitosan nanopolymer were compared in terms of effectiveness against the fungi *Aspergillus flavus*, aflatoxin B1 contamination, and lipid peroxidation. The best result was obtained with the nanoencapsulated material that showed antioxidant activity and completely inhibited the fungal growth and the production of the aflatoxin (Upadhyay et al. 2021).

Thyme EO was evaluated in nanoencapsulated and bulk forms to compare their antioxidant and antibacterial activities. It was observed a decrease in the antioxidant activity and in the ability to inhibit the bleaching of β-carotene after the nanoencapsulation. However, both free and nanoencapsulated thyme EO can be used as safe food preservatives (Jemaa et al. 2018).

Poly(lactic acid) nanocapsules containing lemongrass (*Cymbopogon citratus*) EO were evaluated in the control of the fruit rot in post-harvest apples, presenting good *in-vitro* activity against *Colletotrichum acutatum* and *C. gloeosporioides*. The in-vivo assay showed that apples treated with encapsulated EO had three times less rot lesions than those treated with non-encapsulated EO (Antonioli et al. 2020).

Cumin (*Cuminum cyminum*) EO nanoencapsulated with chitosan was investigated as an alternative to the growth-promoting antibiotic in broiler diets (Amiri et al. 2020). Later, the effect was potentiated by using garlic EO nanoencapsulated with chitosan with a significantly improved antibacterial and antioxidant activity, especially if compared with free garlic acid EO (Amiri et al. 2021).

The combination of carvacrol, bergamot (*Citrus bergamia*), and grapefruit (*Citrus* × *paradisi*) EOs was nanoencapsulated in β-cyclodextrins to ice storage seabream (*Sparus aurata*) fish. The data obtained showed antimicrobial and antioxidant properties of the combined OEs. The shelf life of the fish stored at 2°C was extended up to four days. The sensory attributes were also improved during storage (Navarro-Segura et al. 2019).

Bio-based films, coatings, and nanoencapsulation with EOs can exhibit various characteristics such as biodegradability, biocompatibility, and even edibility, depending on the formulation and production processes employed. This versatility triggers out new application opportunities, bolstering the potential for their utilization and positively impacting sustainability efforts (Kumar et al. 2020, Moalla et al. 2021).

Among all characteristics, the thickness of films is a crucial factor that influences their mechanical, barrier, and migration properties. It is evidenced by the enhanced performance of the more uniform polymeric materials (Ferreira et al. 2022). Furthermore, the properties of EOs play a significant role in the production of films, coatings, and nanoencapsulated products (Fig. 1). The specific characteristics of EOs can vary based on their chemical composition and matrix components. However, most of the works do not yield substantial information explaining how EO properties are affected, even when considering different film thickness attributes.

CONCLUSION

There is a wide possibility for using EOs as natural additives in the development of films, coatings and nanoencapsulated materials. These EOs act not only as an antioxidant, antibacterial, and antifungal agents; they can also improve tensile strength, elongation, water vapor permeability, oxygen permeability in films, for example. Clove, cinnamon, and oregano EOs are among the most studied additives in the production of films, coatings, and nanoencapsulated materials. Comparisons between free and nanoencapsulated EOs have revealed the nanoencapsulation technique as a beneficial strategy to improve the stability of the EOs and, therefore, their efficiency as antimicrobial agents. This contrasts with the low solubility in water, and the high susceptibility to oxidation and volatilization of the free EOs. The utilization of all these EOs has resulted in excellent natural additives of interest to produce biodegradable and ecological packaging for food safety and quality maintenance.

CONFLICT OF INTEREST

Nothing to declare.

AUTHORS' CONTRIBUTION

Conceptualization: Cortez-Vega, W. R.; **Supervision:** Cortez-Vega, W. R.; **Formal analysis:** Cesca, R. S., Fonseca, G. G., Paz, M. F. and Cortez-Vega, W. R.; **Investigation:** Cesca, R. S., Fonseca, G. G., Paz, M. F. and Cortez-Vega, W. R.; **Writing – original draft preparation:** Cesca, R. S. and Fonseca, G. G.; **Writing – review and editing:** Cesca, R. S. and Fonseca, G. G.

DATA AVAILABILITY STATEMENT

The datasets generated and/or analyzed during the current study are available from the corresponding author on request.

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