AppliedChem

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Review

Essential Oils in Postharvest Treatment against Microbial Spoilage of the *Rosaceae* Family Fruits

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Abstract: Fruits undergo numerous chemical, physical, and microbiological changes during storage that shorten their postharvest life, reducing shelf-life and boosting food loss. Food quality and safety are seriously threatened by postharvest infections, one of the factors behind postharvest deterioration and mycotoxin contamination in fruits. The control of postharvest deterioration is a big concern because there are few management methods available. Several attempts have been undertaken to prevent the microbial degradation of fresh food at the postharvest stage without using synthetic fungicides, which are dangerous for the environment and people's health. A good substitute for synthetic fungicides among them is the use of natural plant compounds, such as essential oils included or not included in the edible coatings. This review's aim was to collect information from the scientific literature on the biological activity of essential oil, with or without edible coatings, against pathogens that cause the postharvest spoilage of many fruit belonging to *Rosaceae* family in order to develop appropriate substitute tactics for synthetic fungicides in the treatment of postharvest fruit diseases. Advances and obstacles surrounding emerging methods that may be useful for enhancing the effectiveness and dependability of essential oils were evaluated.

Keywords: postharvest fungi; phytochemicals; botanicals; plants extract; postharvest disease stone and pome fruits

Citation: Magri, A.; Curci, M.; Battaglia, V.; Fiorentino, A.; Petriccione, M. Essential Oils in Postharvest Treatment against Microbial Spoilage of the *Rosaceae* Family Fruits. *AppliedChem* **2023**, *3*, 196–216. https://doi.org/10.3390/appliedchem3020013

Academic Editors: Antony C. Calokerinos, Nikos Lydakis-Simantiris and Spyros Grigorakis

Received: 9 March 2023
Revised: 24 March 2023
Accepted: 28 March 2023
Published: 3 April 2023

1. Introduction

Fruits are abundant in vitamins, minerals, fiber, and other nutrients that the human body needs, and their consumption is growing worldwide. However, postharvest pathogens appear to be the primary cause of the fruit's reduced shelf-life and loss, also leading to financial losses [1]. Most postharvest pathogens are unable to penetrate directly through the fruit cuticle, requiring a wound for their penetration. In general, these wounds are inflicted during harvest, transport, packing, and storage. Several postharvest pathogens have been recorded in pome and stone fruit of the *Rosaceae* family, including rot caused by *Rhizopus stolonifer* [2–5], brown rot caused by *Monilinia fructicola*, *M. fructigena*, and *M. laxa* [2,5–10], gray mold caused by *Botrytis cinerea* [2,3,9–11], anthracnose caused by *Colletotrichum gloeosporioides* and *C. acutatum* [2–4,12,13], blue mold caused by *Penicillium expansum* [2,11,14,15], and bull's eye rot caused by *Neofabraea vagabunda* [14], which are the main aggressive diseases that cause postharvest rot. In addition, other pathogens have been described, such as *Diaporthe* spp, *Neofusicoccum yunnanense*, and *Diplodia* spp. in apple [16], *Penicillium* spp., *Talaromyces minioluteus*, and *T. rugulosus* in pear [15], *Mucor piriformis*, *Rhizoctonia solani*, *Phytophthora* spp., and *Fusarium oxysporum* in strawberry [3,12], *Gibberella avenacea* and *Alternaria alternata* in apple and peach [12], *Pestalotiopsis clavispora* in

loquat [17], and *Aspergillus niger*, *Cladosporium herbarum*, *Stemphylium* spp., *Geotrichum* spp., *Sclerotinia* spp., *M. piriformis*, *Coryneum carpophilum*, and *Fusarium* spp. in stone fruits [18]. Synthetic antimicrobial substances are usually used to eradicate or slow the growth of pathogens that cause postharvest food deterioration. Since they present several toxicological challenges and are not safe for human consumption, the use of chemical antimicrobial agents as food preservatives has worried consumers [19]. For this reason, during the past two decades, the scientific community aimed to implement knowledge of natural antimicrobial agents such as essential oils (EOs), studying their distinctive physicochemical characteristics and wide range of biological activities [20]. As a potential alternative for industrial chemicals, the U.S. Food and Drug Administration (USFDA) classifies them as Generally Recognized as Safe (GRAS) [21]. EOs can be extracted from different plant organs, including fruits, bark, seeds, pulp, peel, roots, and, in some cases, entire plants [22]. Currently, EOs are used in the food industry as flavoring agents, but their potential as a natural food-grade preservative has not been properly investigated. Several studies have been carried out in in vitro settings. The concentration of EOs and associated constituents, which are necessary to prevent microbial development, is often greater in food than in culture media. Often, the quantities that are beneficial against the disease may nevertheless occasionally be phytotoxic and lead to the additional chemical degradation of treated food. New strategies, such as inclusion in nanoparticles or coatings, to reduce the impact of essential oils on the fruit should be investigated. Due to their inherent antimicrobial characteristics, EOs could offer a useful tool for food preservation [23]. The EOs are made up of several different classes of chemicals, containing aromatic hydrocarbons (phenylpropanoids), terpenes (monoterpenes and sesquiterpenes), esters, lactones, alcohols, aldehydes, and ketones [24]. Due to the intricacy of their chemical composition, it is difficult to identify the most effective molecule responsible for the antimicrobial action of EOs; this propriety is probably correlated to the synergistic effect of all of the EO chemicals, and not just one molecule [25]. Many EOs were discovered to be helpful against gray mold and brown rot on nectarines, peaches, plums, pears, and strawberries [9,26–28]. Several studies reported the effectiveness of EOs against blue mold (*P. expansum*) [29,30], gray mold [31–34], and bitter rot [35], as well as *Alternaria* spp. and *Fusarium* spp. rots [36].

In this paper, the use of EOs, incorporated or not incorporated in edible coating, to prevent the microbial deterioration of fruits belonging to *Rosaceae* family during postharvest was reviewed. The results presented in this review could help the formulation of new and sustainable solutions for fruit storage based on EOs.

2. Postharvest Pathogens

The main postharvest pathogens responsible for serious damage to stone and pome fruit, against which the antimicrobial activities of EOs have been assayed in vitro and in vivo, are shown in Table 1.

Table 1. The main postharvest pathogens and their abbreviation and types of fruits and diseases [2–18].

Pathogens	Abbreviations	Fruit	Disease
Alternaria alternata (Fr.) Keissl. (Basionym: *Torula alternata* Fr.)	AA	Stone	Brown spot
Aspergillus carbonarius (Bainier) Thom (Basionym: *Sterigmatocystis carbonaria* Bainier)	AC	Pome	Bunch rot
Aspergillus flavus Link	AF	Stone	Green mold
Aspergillus niger Tiegh.	AN	Stone	Black mold
Botrytis cinerea Pers.	BC	Pome–Stone	Gray mold
Colletotrichum acutatum J.H. Simmonds	CA	Pome–Stone	Antrachnose
Colletotrichum gloeosporioides (Penz.) Penz. & Sacc. (Basionym: *Vermicularia gloeosporioides* Penz.)	CG	Pome–Stone	Antrachnose
Colletotrichum nymphaeae (Pass.) Aa (Basionym: *Ascochyta nymphaeae* Pass.)	CN	Stone	Antrachnose
Monilinia fructicola (G. Winter) Honey (Basionym: *Ciboria fructicola* G. Winter)	MFC	Stone	Brown rot
Monilinia fructigena (Pers.) Honey (Basionym: *Torula fructigena* Pers.)	MFG	Pome–Stone	Brown rot
Monilinia laxa (Aderh. & Ruhland) Honey (Basionym: *Sclerotinia laxa* Aderh. & Ruhland)	ML	Pome–Stone	Brown rot
Mucor piriformis A. Fisch.	MP	Stone	Brown rot
Penicillium expansum Link	PE	Pome–Stone	Blue mold
Penicillium notatum Westling (current name: *Penicillium chrysogenum* Thom)	PN	Stone	Green mold
Rhizopus microsporus Tiegh.	RM	Stone	Rotten spots
Rhizopus stolonifer (Ehrenb.) Vuill. (Basionym: *Mucor stolonifer* Ehrenb.)	RS	Pome–Stone	Rotten spots
Trichothecium roseum (Pers.) Link (Basionym: *Trichoderma roseum* Pers.)	TR	Pome	Core rot

3. EOs' Chemical Composition

Botanical active ingredients for plant-based goods are obtained differently from synthetic chemical active ingredients. Whereas botanical active ingredients are obtained via the processing of biologically derived material, synthetic chemicals are created through chemical processes [37]. In botanicals, there is a subcategory that includes EOs, defined according to the U.S. Environmental Protection Agency (EPA): "*Essential oils are mixtures of natural substances that come from various parts of plants, such as flowers, fruits, and wood. They are responsible for the distinctive odor or flavor of the plant they come from*". Plant-derived EOs are thought to be non-phytotoxic substances and may be useful as phytochemicals to protect crops. They include intricate combinations of active secondary metabolites that have antibacterial, allelopathic, antioxidant, and bioregulatory activities [38]. The number of molecules, the stereochemical characteristics, and the extraction method affect the chemical composition of EOs. The quality, quantity, and content of the extraction products may vary according to the environment, soil composition, plant organs, age, and vegetative cycle stage (chemotypes) [39]. Due to their verified safety, widespread public acceptability, and potential for several purposes, EOs from various plants are garnering interest.

Over 300 distinct chemicals constitute EOs, although most of them are volatile substances with molecular weights below 1000 Da (often 300 Da). In contrast to other compounds, which are present in trace levels, a select few chemicals are essentially present as large ones at roughly 20–70% (Table 2) [40].

A large class of chemicals in EOs that are known to have antimicrobial action are terpenes and terpenoids. Terpenes represent a wide group of hydrocarbons, characterized by different chemical structures, constructed from isoprene units C_5. They are classified into numerous categories based on the number of isoprenic units, including emiterpenes (C_5), monoterpenes (C_{10}), sesquiterpenes (C_{15}), diterpenes (C_{20}), sesterterpenes (C_{25}), triterpenes (C_{30}), and tetraterpenes (C_{40}).

Terpenoids are also found in EOs. They are defined as terpene molecules with a methyl group that has been transposed or eliminated. The terpenoids can be oxidized and found as esters, aldehydes, ketones, alcohols, ethers, and epoxides. Approximately 90% of EOs include monoterpenes, which make up most of their constituent parts. These often have a nice odor, and they are volatile. The monoterpenes are significantly involved in the synthesis of a wide range of structures. Carvacrol, geraniol, eugenol, thymol, linalyl acetate, linalool, citronellal, citronellol, and terpineol are examples of terpenes and terpenoids (Figure 1). Thymol and carvacrol are the two main components of thyme and oregano EOs. Bouchra et al. [41] demonstrated that the essential oil of *Origanum compactum* Benth., which contains carvacrol (58.1%), *p*-cymene (11.4%), and thymol (9.0%) as major components, was more toxic against *BC*. Additionally, according to Pérez-Alfonso et al. [42], thymol and carvacrol demonstrated substantial antifungal efficacy against postharvest pathogens such as *Penicillium digitatum*, *P. italicum*, *Fusarium* spp., and *Aspergillus* spp. Citronellol, octanal, citral, decanal, nonanal, β-pinene, linalool, and γ-terpinene, present at a high quantity in citrus EOs, showed antifungal properties against *P. italicum*, whereas octanal, decanal, nonanal, limonene, citral, α-terpineol, and linalool showed antifungal properties against *P. digitatum* [43]. According to Cai et al. [44], menthol caused serious membrane lipid peroxidation and the generation and accumulation of reactive oxygen species in *Geotrichum candidum* var. *citri-aurantii*, which led to the breakdown of the integrity of the plasma membrane of the pathogen.

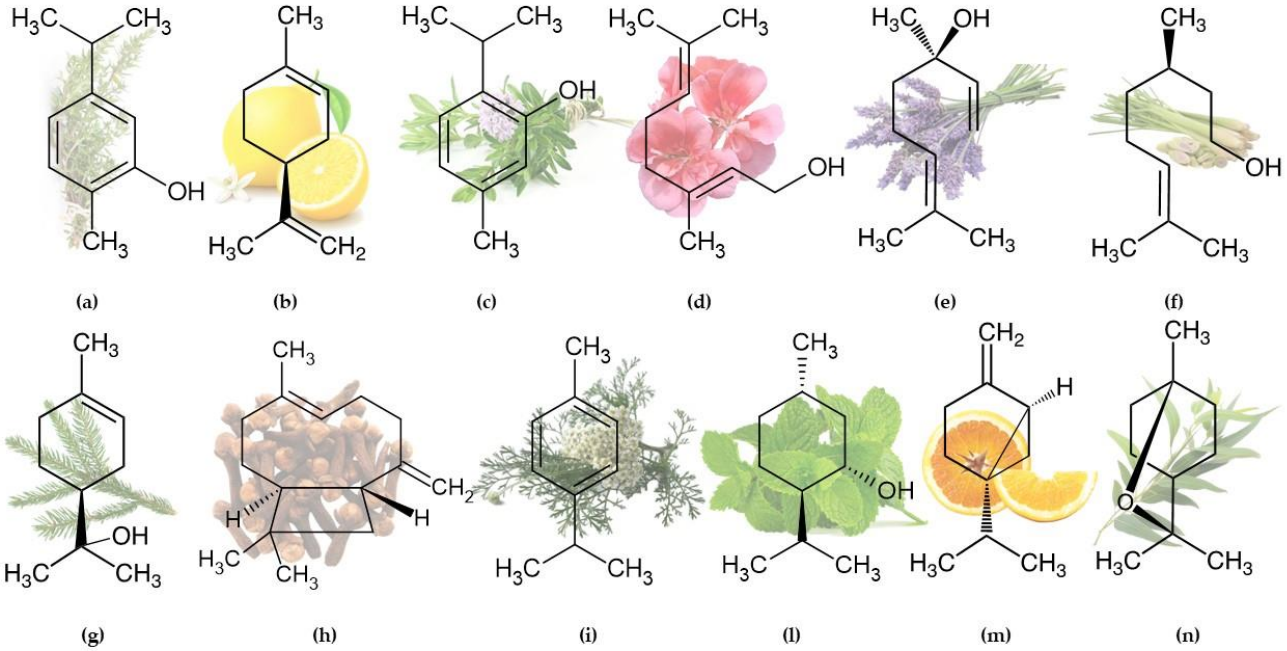

Figure 1. The chemical structures of significant and major terpenoids and monoterpenes contained in EOs: (**a**) carvacrol, (**b**) (−)-limonene, (**c**) thymol, (**d**) geraniol, (**e**) (−)-linalool, (**f**) (+)-citronellol, (**g**) (−)-*a*-terpineol, (**h**) *β*-caryophyllene, (**i**) *p*-cymene, (**l**) (−)-menthol, (**m**) (+)-sabinene, and (**n**) 1,8-cineole.

The second category of compounds mainly present in EOs was phenylpropanoids, which consist of aromatic substances such as benzyl, phenylethyl, and phenylpropyl. They are biosynthesized by the shikimate pathway. Typically, they have a benzene ring (C_6H_6) bonded to a three-carbon chain. Important phenylpropanoids and derivatives are anethole, estragole, cinnamaldehyde, eugenol, safrole, apiol, vanillin, and benzaldehyde (Figure 2). Kalleli et al. [45] demonstrated that fennel essential oil (composed of 78% trans-anethole) reduced the severity of the infection caused by *Fusarium oxysporum* f. sp. *lycopersici* by 98% in treated plants with the oil, eight weeks after inoculation. The cinnamaldehyde and estragole had inhibitory activity against *Pseudomonas syringae* pv. *actinidiae* at a concentration of 1.250 and 2.500 ppm [46]. The *Ocimum sanctum* L. essential oil, which has a wide range of fungitoxic properties and was also found to be effective in lowering the incidence of *AF* in raw materials (roots) of *Rauvolfia serpentina* (L.) Benth. Ex Kurz during storage, was found to be primarily composed of eugenol, followed by *β*-caryophyllene and germacrene D [47]. The growth of *CA*, *CG*, and *Botryodiplodia theobromae*, three important postharvest pathogens of fruits, was reduced in vitro by the EOs of *Piper auritum* Kunth and *P. holtonii* C.DC., which were primarily composed of safrole and apiol [48]. Vanillin treatment in vivo and in vitro increased the *BC* and *AA* membrane permeability, inhibiting the pathogenicity-related enzyme activities and reducing the infection ability of fungi [49].

Table 2. Plant material for EOs extraction and main components [50].

Scientific Name	Common Name	Abbreviation	Organs	Principal Compounds
Acorus calamus L.	Calamus oil	CaEO	Flowers and leaves	α-asarone, (*E*)-methylisoeugenol, methyleugenol and β-asarone
Allium sativum L.	Garlic oil	GEO	Bulb	Allyl methyl trisulfide, diallyl disulfide, diallyl trisulfide, and allyl methyl disulfide
Aloysia citriodora Kunth.	Lemon Verbena oil	LVEO	Leaves	Geranial, neral, spathulenol, and limonene
Alpinia officinarum Hance	Galangal oil	GalEO	Rhizomes	1,8-cineole, α-fenchyl acetate, β-myrcene, and β-ocimene
Artemisia argyi H.Lév. & Vaniot	Artemisia oil	ArEO	Leaves	Eucalyptol, β-pinene, camphor, and artemisia ketone
Cinnamomum zeylanicum L.	Cinnamon oil	CEO	Barks	Cinnamaldehyde, benzaldehyde, and trans-cinnamyl acetate
Citrus aurantiifolia L.	Lime oil	LiEO	Fruits	Limonene, α-terpineol, terpinen-4-ol, and 1,8-cineole
Citrus limon L.	Lemon oil	LeEO	Fruits	Limonene, citrale, citronellal, geranyl acetate
Cortex dictamni Turcz.	Cortex oil	CoEO	Leaves	Germacrene D, terpinolene, (Z)-β-ocimene, and β-caryophyllene (7.74%)
Cymbopogon citratus L. *Cymbopogon winterianus* Jowitt	Lemongrass oil	LgEO	Leaves	Citral, isoneral, isogeranial, and geraniol
Cymbopogon martini (Roxb.) Wats.	Palmarosa oil	PalEO	Flowers and leaves	Geraniol, geranylacetate, farnesol, and nerolidol
Eucalyptus globulus Labill. *Eucalyptus camaldulensis* Dehnh. *Eucalyptus staigeriana* F.Muell. ex Bailey	Eucalyptus oil	EuEO	Leaves	Eucalyptol, *p*-cymene, α-pinene, and β-limonene
Foeniculum vulgare Mill.	Fennel oil	FEO	Seeds and fruits	Trans-anethol, fenchone, estragole, and limonene
Laurus nobilis L.	Laurel oil	LaEO	Leaves	1,8-cineole, sabinene, α-pinene, and linalool
Lavandula officinalis L.	Lavander oil	LEO	Flowers and leaves	Linalyl acetate, α-terpineol, and borneol
Lippia sidoides Cham.	Pepper-rosmarin oil	PREO	Leaves	1,8-cineole, sabinene, α-terpineol, and α-pinene
Malaleuca ericifolia Sm.	Rosalina oil	RosEO	Leaves	1,8-cineole, α-pinene, γ-terpinene, and terpinen-4-ol
Mentha piperita L.	Peppermint oil	PEO	Leaves	Menthol, menthone, menthofuran, and cis-carane
Mucuna pruriens (L.) DC.	Mucuna pruriens oil	MPEO	Leaves	(E)-2-hexenal, linalool, 1-hexanol, and trans-dehydroxylinalool oxide
Ocimum americanum L.	Ocimum americanum	OAEO	Leaves	1,8-cineole, (E)-γ-bisabolene, β-bisabolene, and eugenol
Origanum majorana L.	Majorana oil	MEO	Flowers and leaves	4-terpineol, cis-thujan-4-ol, δ-terpinene, and α-terpinene
Origanum vulgare L.	Oregano oil	OEO	Flowers and leaves	Carvacrol, *p*-cymene, and linalool
Pelargonium graveolens	Geranium oil	GaEO	Flowers and leaves	Citronellol, geraniol, citronellyl formate, and linalool
Pimenta pseudocaryophyllus (Gomes) L.R. Landrum	Pimenta oil	PPEO	Leaves	Methyl eugenol, neral, geranial, and (E)–methyl isoeugenol
Rosmarinus officinalis L.	Rosemary oil	REO	Flowers and leaves	*p*-cymene, camphor, limonene, and myrcene
Salvia officinalis L.	Sage oil	SaEO	Flowers and leaves	α-thujone, β-thujone, camphor, and camphene
Satureja hortensis L.	Summer savory oil	SSEO	Flowers and leaves	Carvacrol, *o*-cymene, linalool, and caryophyllene oxide
Sesamum indicum L.	Sesamum oil	SeEO	Leaves and seeds	Linoleic acid, oleic acid, and palmitic and stearic acid
Syringa vulgaris L.	Lilac oil	LLEO	Flowers and leaves	Ocimene, benzyl methyl ether, 1,4-dimethoxybenzene, and indole
Syzygium aromaticum ((L.) Merr. & L.M.Perry, 1939) *Eugenia caryophyllata*	Clove oil	ClEO	Leaves and seeds	Eugenol, β-caryophyllene, α-humulene, and eugenyl acetate
Thymus vulgaris L.	Thyme oil	TEO	Flowers and leaves	Thymol, cis-3-hexenyl acetate, *p*-cymene, and carvacrol
Verbena officinalis L.	Vervain oil	VEO	Flowers and leaves	Limonene, 1,8-cineole, pathuleno1, and caryophyllene oxide
Zanthoxylum bungeanum Maxim	Zanthoxylum bungeanum oil	ZBEO	Flowers and leaves	Terpineol-4-ol, (-)-β-pinene, γ-terpinene, and terpinyl acetate
Zataria multiflora Boiss	Zataria oil	ZMEO	Flowers and leaves	Thymol, carvacrol, *p*-cymene, and γ-terpinene
Mentha spicata L.	Mint oil	MiEO	Flowers and leaves	Linalyl acetate, linalool, carvone, and limonene
Litsea cubeba Pers.	Litsea oil	LitEO	Flowers and leaves	Geranial, neral, limonene, and β-thujene

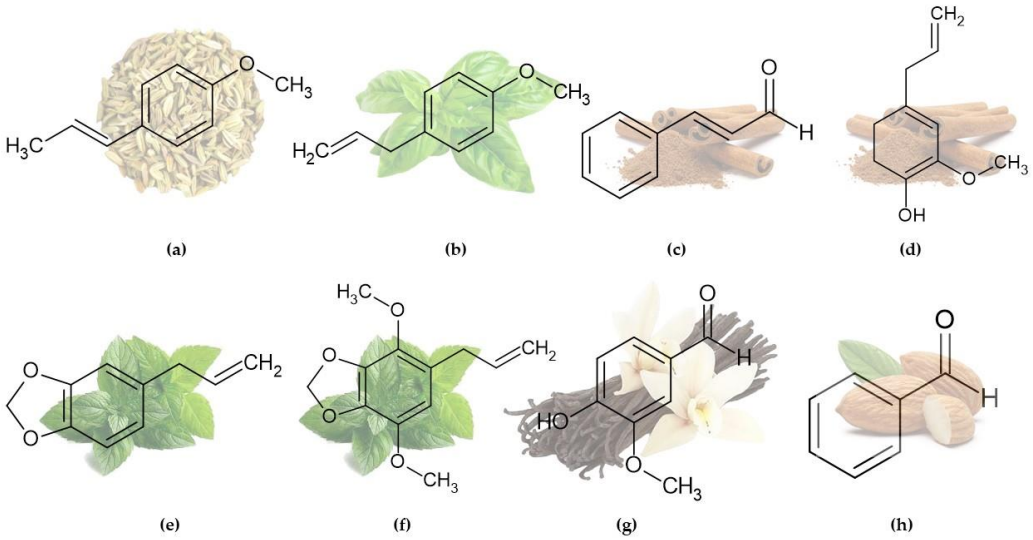

Figure 2. The chemical structures of significant and major phenylpropanoids and derivatives contained in EOs: (**a**) anethole, (**b**) estragole, (**c**) cinnamaldehyde, (**d**) eugenol, (**e**) safrole, (**f**) apiol, (**g**) vanillin, and (**h**) benzaldehyde.

4. Essential Oils' Effects on Human Health and the Environment

In addition to increasing costs, handling risks, worries about plant protection product (PPP) residues in food, and threats to human health and the environment, the extensive use of PPPs has serious negatives [51]. Finding better substitutes for PPPs made of synthetic chemicals has become more popular because of growing public awareness of these concerns. In line with the current trend of investigating new options for extending storage life, techniques that reduce horticultural product degradation while minimizing negative effects on human health or the environment must be prioritized [52]. Natural plant additives with pesticidal and antimicrobial action are one such alternative; they tend to be less poisonous to mammals, have fewer negative impacts on the environment, and are well-liked by the general population. EOs and other natural plant products are regarded as more biodegradable than synthetic substances. There are significant worries about the potential negative impacts of EOs on human health and the environment, which are still under investigation. EOs are extracted using a variety of contemporary and conventional procedures, including steam distillation, hydrodistillation, ultrasonic, ohmic, and microwave-aided hydrodistillation, and supercritical fluid extraction [53,54]. Conventional techniques have a few drawbacks, including a lengthy extraction process, low efficiency, solvent toxicity, and a detrimental effect on the environment. Modern techniques are now preferred over traditional approaches or extraction methods because they are quicker, more effective, use less energy, and produce more EOs with a low negative effect on the environment [55].

To date, there are more studies describing the beneficial effects of EO consumption on human health than there are studies attesting to their toxicity. EOs are typically known to be non-toxic for humans and other mammals, as they are quickly absorbed and processed in the liver and eliminated by the kidneys [56]. Ezeorba et al. [57] reported that garlic EOs possessed interesting medical properties, such as antimicrobial, cardio-protective, anti-cancer, anti-Alzheimer, anti-diabetic, and immunomodulatory activities. According to studies by Loizzo et al. [58] and Koul et al. [59], limonene, which is the compound that most characterizes lemon and citron EOs, had lymphotonic, powerful diuretic, healing, scalping tonic, antifungal, anti-moth decongestant, antiseptic respiratory, purgative, relaxing, and comforting actions. Menthol and menthone, mainly found in mint essential oil, has shown tonic, stimulant, decongestant, anesthetic and analgesic, cooling, and anti-inflammatory properties [60]. Cinnamon essential oil, particularly cinnamaldehyde, was described as a potent antibacterial, antifungal, antiviral, anticoagulant, and uterine tonic [61,62].

5. Use of Essential Oils to Control Postharvest Microbial Spoilage

The antimicrobial properties of EOs have been described in several studies. EOs have been shown to have a wide range of antifungal properties and have the advantage of being environmentally friendly [59,63,64]. EOs are natural compounds that show antifungal activity, and they can be used instead of synthetic fungicides. Several studies demonstrated that EO activity appears to be stronger in vitro than in vivo, which is necessary to confirm the in vitro results with in vivo tests.

There are several modes of action of EOs that make them natural fungicides, e.g., they interact with ergosterol, which is essential for maintaining cell integrity as well as fungal function, viability, and growth; they can pass through the lipid bilayer of the cell membrane, increasing permeability and causing cell death or the inhibition of fungal germination and sporulation; and phenolic compounds interact with porins, causing ion leakage and cell breakdown [65–67].

Due to their low permeability, uncontrolled volatility, and low solubility, the commercialization of EOs is restricted. To avoid these limitations, there are different strategies, such as developing proper formulation by the encapsulation of EOs in nanoemulsion or developing edible coatings [68,69]. EO concentrations require careful optimization depending on fruit crops. Although, in in vitro tests, the efficacy is directly correlated with the EO concentration, when applied to fruit, EO vapors could have phytotoxic effects, which reduce the treatment efficacy [9]. Many factors, such as the chemical composition,

environmental factors, targeted pathogens, botanical sources, and type of food to be treated can affect the antimicrobial action of EOs [70,71]. Below are studies on the effectiveness of EOs in vitro and in vivo on postharvest pathogens responsible for fruit decay and food wastage, divided by pome (apple and pear) and stone fruits (sweet cherry, apricot, peach, strawberry, and plum).

5.1. Pome Fruits

Fresh fruits are a favorable habitat for pathogenic and spoilage fungi and bacteria due to their concentration of nutrients, such as sugars, and the high moisture [72,73]. All bioassays cited in this paragraph are reported in Table 3.

Table 3. Overview of antimicrobial activity of essential oils, with or without edible coating, in pome fruits.

Fruit	Pathogens	EO	Coating	EOs Application Method	Reference
Apples	*Aspergillus carbonarius*	Cinnamon	Na-alginate coating	Inclusion in coating	[74]
	Botrytis cinerea	Oregano, savory, and thyme	Starch–gellan coating	Dropped	[27]
		Lime, lemon, and lemongrass		Thermofogging treatment	[31]
		Thyme and savory		Dropped	[26]
		Thyme		Dropped	[75]
		Fennel, thyme, lavender, neem, pennyroyal, salvia and asafetida		Dropped	[76]
		cinnamon, pimento, and laurel		Spray	[33]
		Cinnamomum zeylanicum, *Zataria multiflora*, and *Satureja khuzestanica*	Macro-sized bacterial cellulose coating emulsion		[77]
		Pelargonium graveolens	Films were prepared with SSOS, chitosan	Volatile activity test	[78]
		Fennel oil		Vapor	[79]
		Thyme and savory		Fumigation	[34]
	Colletotrichum acutatum and *C. gloeosporioides*	Lemongrass	Poly(lactic acid) nanocapsules	Inclusion in nanocapsules	[80]
	Monilinia laxa and *M. fructigena*	*Eucalyptus radiata* ssp. *Mentha pulegium*, *Rosmarinus officinalis*, *Origanum compactum*, *Lavandula angustifolia*, *Syzygium aromaticum*, *Thymus vulgaris*, *Citrus aurantium*, and *Citrus sinensis*		Wound application	[70]
	Penicillium expansum	*Cinnamomum zeylanicum*, *Zataria multiflora*, and *Satureja khuzestanica*	Macro-sized bacterial cellulose coating emulsion		[77]
		Pelargonium graveolens	Films were prepared with SSOS, chitosan	Volatile activity test	[78]
		Fennel		Vapor	[79]
		Oregano, savory, and thyme	Chitosan and sodium alginate	Dropped	[27]
		Cinnamon		Coating	[81]
		Exogenous EO decanal		Dropped	[82]
	Rhizopus stolonifer	*Pelargonium graveolens*		Volatile activity test	[78]
	Trichothecium roseum	Fennel	Films were prepared with SSOS, chitosan	Vapor	[79]
Pears	*Aspergillus carbonarius*	Cinnamon	Na-alginate coating	Inclusion in coating	[74]
	Botrytis cinerea	Cinnamon, rosemary, and marjoram EOs		Dropped	[83]
	Penicillium expansum	Cinnamon, rosemary, and marjoram EOs		Dropped	[83]
		Eucalyptus and rosemary		Vapor	[28]
		Exogenous EO decanal		Dropped	[82]

The major fungal pathogens that have been associated with losses in the quality of pectin-rich fruits, such as pear and apple fruits, include *PE*, the causal agent of blue mold, and *BC*, the causing factor of gray mold [84–87].

The antifungal effects, both in vitro and in vivo, of the rosemary, eucalyptus, thyme, cinnamon, and marjoram EOs and their combination against *BC* and *PE*, as well as their effects on quality attributes, were highlighted, and their possible use as natural fungicides in the fresh fruit industry for postharvest disease control was encouraged [28,83]. Specifically, the in vitro treatment with 300 μL L^{-1} eucalyptus EO (EuEO,) 300 μL L^{-1} rosemary EO (REO), and their mixture revealed a decrease in spores germination and fungal colonies of *PE*. Their application in vapor form on fresh pears in vivo led to an increase in the

respiration rate and a reduction in the growth of *PE* lesions [28]. Nikkhah [83] investigated the antifungal activity of thyme, cinnamon, rosemary, and marjoram EOs and the synergistic activity of their combinations. In vitro, thyme EO (TEO) and cinnamon EO (CEO) demonstrated the highest antifungal activity and the lowest minimum inhibitory concentration (MIC) against *PE* and *BC*. A remarkable synergistic interaction was observed in the thyme/cinnamon dual combinations against both mold species. Fractional inhibitor concentration analysis (FICi) and in vivo treatments indicated that the triple combination of cinnamon/majoran/thyme produced the most synergistic antifungal effect. In accordance with the previously mentioned study, in vitro experiments demonstrated that the CEO significantly inhibits *PE*. In vivo, the multi-layer coating, formed by chitosan (1% w/v), sodium alginate (1% w/v), and CEO (4% v/v), showed a more significant and lasting inhibition of *PE* in two varieties of apples, 'Guoguang' and 'Huangyuanshuai', compared to a single-layer coating with chitosan and CEO or sodium alginate and CEO [81].

PE produces patulin, a mycotoxin hazardous to consumer health. Zhou et al. [82] demonstrated that exogenous EO decanal in in vitro tests (0.12 g L^{-1}) reduced the *PE* growth and, in in vivo tests (0.24 g L^{-1}), controlled the effect against blue mold rot on apples and pears; moreover, EO decanal inhibited patulin production.

Apple is one of the most important fruits in international trade and can suffer severe postharvest losses during transport and storage. *BC*, which causes gray mold, is one of the main pathogens causing postharvest losses [88]. The use of TEO at a 1% v/v concentration showed high efficiency in reducing the damage and incidence of *BC* symptoms and could be used as an effective postharvest treatment in stored apples. Furthermore, treatment with TEO increases the expression of the specific pathogenesis-related gene PR-8, suggesting an induction of resistance against *BC* through the priming of defense responses in apple fruit [26]. In vitro, the application of Zataria EO (ZMEO, 300–1200 µL L^{-1}) and CEO (300–1200 µL L^{-1}) presented inhibitory effects on *BC* and *PE*. This result was confirmed by in vivo tests, where the lesion diameter in inoculated apples was reduced by the ZMEO (600–1200 µL L^{-1}) and CEO (600–1200 µL L^{-1}) [77]. Sadat Razavi et al. [77] demonstrated that BCNCs/GelA-CEO (75–2400 µL L^{-1}) emulsions decreased *BC* and *PE* lesions on inoculated apples, with a better performance of non-encapsulated EO. The strongest effect was shown at the highest concentration of CEO, with which lesions on the fruit skin were barely detectable (Figure 3).

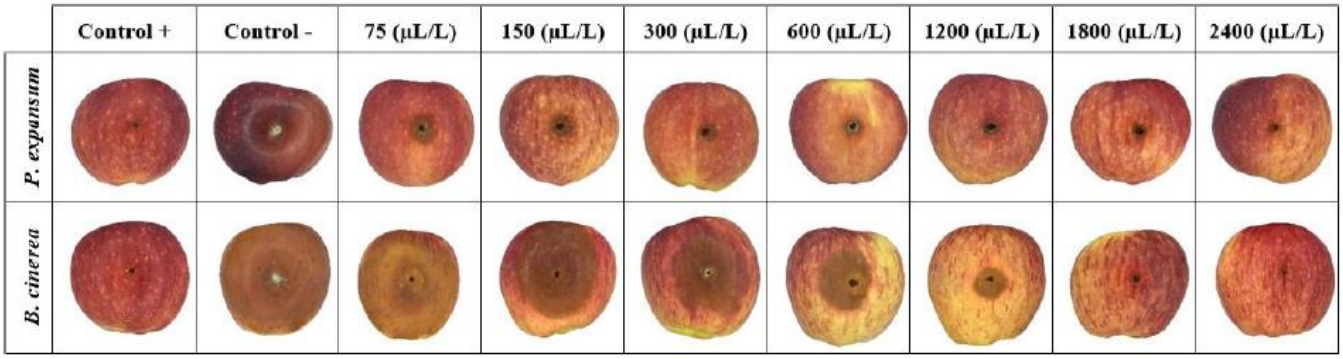

Figure 3. *Botrytis cinerea* and Penicillium expansum lesions on inoculated apples treated with cinnamon essential oil. Reproduced with permission from Sadat Razavi, M.; Golmohammadi, A.; Nematollahzadeh, A.; Ghanbari, A.; Davari, M.; Carullo, D.; Farris, S. Foods 2022.

The incorporation of fennel EO (FEO) in a starch sodium octenyl succinate/chitosan film (mass ratio SSOS/glycerol/FEO/chitosan was 1:0:2:1:0.5) for apple fruit showed good antifungal activity, in vivo and in vitro, against *BC*, *TR*, and *PE*. Moreover, the coating reduced the respiration rate and weight loss whereas the firmness, peel lightness, soluble solids, and titratable acid content were maintained [79].

The treatment of the apple cultivar 'Opal' with 1% TEO and summer savory EO (SSEO) by fumigation shows significant gray mold control after 60 days of storage at 1 °C,

confirming the results obtained in vitro, where the application of thyme and savory EOs significantly reduced the growth of *BC* [34].

An application that allows for a uniform distribution of EOs and enables a small quantity to be used is the thermofogging treatment. Applying lime EO (LiEO), lemon EO (LeEO), and lemongrass EO (LgEO) on the 'Golden Delicious', 'Pink Lady', and 'Granny Smith' cultivars at a concentration of 0.016–1% results in a significant inhibition of the mycelial growth and spore germination of *BC*, resulting in a reduction in the decay of the apples [31].

In contrast, Sapper [75] evaluated that adding a starch–gellan (80:20 *w*/*w*) coating formulation with the incorporation of TEO (0.25 and 0.5 per g of polymer) directly or encapsulated in lecithin promotes the respiration rates and quotient in apples, but no antifungal action against *BC* was observed in vivo, despite in vitro tests and other studies proving the opposite.

Geranium essential oil exhibits significant antifungal activity against *RS*, *PE*, and *BC* in vitro using poisoned food [78]. Despite in vitro tests demonstrating the effectiveness of CEO, pimenta EO (PPEO), and laurel EO (LaEO) against *BC*, these had no significant effects in in vivo tests carried out on 'Connel Red' apples during storage, except for cinnamon extract even at high concentrations [33].

Several studies have shown that the higher the concentration of the essential oil, the greater the inhibition of the mycelium growth of pathogenic fungi, but a concentration of 10% was found to be phytotoxic to fruit [27,80]. Furthermore, the efficiency of EOs in inhibiting *BC* and *PE* depends not only on the concentration and type of oil but also on the cultivar and storage time [27]. The treatment of 'Golden Delicious', 'Granny Smith', 'Red Chief', and 'Royal Gal' apple cultivars with the emulsion at 1% of oregano EO (OEO), SSEO, and TEO dropped into the artificial wound inoculated with *BC* and *PE* showed a decrease in the lesion compared to the control [27].

Other pathogenic fungi causing postharvest disease in pome fruit are *ML* and *MFG*, causal agents of brown rot. These fungi cause blossom blight, twig cankers, fruit rot, and fruit mummification in the orchard [7].

EuEO, mint EO (MiEO), REO, OEO, lavander EO (LEO), clove EO (ClEO), TEO, *Zanthoxylum bungeanum* EO (ZBEO), and OEO were tested, in vitro and in vivo, against *ML* and *MFG*. In vitro tests showed significant antifungal activity of EOs that reduced mycelial growth and spore germination. In in vivo tests, a concentration of 100 µL mL^{-1} of ClEO, TEO, ZBEO, and OEO reduced the brown rot incidence, spore germination, and lesion diameter. Fruit quality parameters such as weight loss, total soluble solids, titratable acidity, firmness, and the maturity index were preserved during storage at 4 °C for 20 days [69].

LgEO has shown antifungal activity against the two fungi responsible for apple bitter rot *CA* and *GC*. In vitro tests demonstrated that the use of poly(lactic acid) nanocapsules containing LgEO at a dosage of 0.1% (*v*/*v*) resulted in fungicidal activity against both phytopathogenic fungi [80]. In vivo tests confirmed that apples treated with encapsulated essential oil show significantly lower bitter rot lesions than those treated with non-encapsulated EO. This is because the active compounds are released more slowly if the EO is contained in nanocapsules and there is a reduction in the necrotic effects by essential oil terpenoids [80].

Adding Na-alginate coating supplemented with 0.3% and 0.9% *v*/*v* CEO to pear and apple slices or wounded skin limits the growth of the fungus *AC* and the production of ochratoxin A. This could be a strategy for limiting spoilage losses and preserving consumer health [74].

Additional studies showed the antimicrobial effect of EOs on total molds, yeast, and mesophilic microorganisms of pome fruit, the main results of which are reported in Table 4. Further analysis may be necessary to evaluate the efficacy against the postharvest pathogens mentioned in this review.

Table 4. Antimicrobial effect of EOs on microorganism responsible for fruit spoilage in pome fruits.

Fruit	Pathogen	Coating	EOs	Results	Reference
Apples	Total molds, yeast and mesophilic microorganisms	Alginate 1% and 2% or Pectin 1% and 2% Ascorbic acid 1% Calcium chloride 1%	Citral 0.15, 0.3% Eugenol 0.1, 0.2% Eugenol 0.1% + Citral 0.15%	Coatings were effective in inhibiting yeasts and molds and reducing ~2 logs CFU/g mesophilic bacteria during 8 days of storage compared to uncoated fruit.	[89]
		Cassava starch 2% Glycerol 0.5%	Cinnamon 0.1, 0.3% Fennel 0.1, 0.3%	Only EC with cinnamon 0.3% was capable of inhibiting pathogens in vitro. EOs at 0.3% provided better color in 4 days	[90]
		Tapioca starch 0.3% + dHG1 0.3% Glycerol 1.7% Ascorbic acid 1%/ Calcium chloride 1%	Cinnamon 0.2%	EO treatments reduced 4 log cycles of mesophilic and psychrophilic bacteria and 3 log cycles reduction in yeasts and molds after 12 days of storage.	[91]
	Total aerobic bacteria, coliforms, yeasts and molds	Alginate 1.29% Glycerol 1.5% Calcium chloride 2% Ascorbic acid 1% Citric acid 1%	Thyme 0.05%, 0.35% and 0.65%	Lower concentrations of EOs were more effective in reducing total aerobic bacteria, coliforms, yeasts, and molds, increasing shelf life in 8 days.	[92]
	Total mesophilic	Pectin 2%, Whey protein 1%, Calcium chloride 2%	Sweet orange 0.1% and 0.15%	EOs at 0.15% slightly reduced (>1 log cycle) total mesophilic counts.	[93]
Pears	Total mould and yeasts	-	Seaweed 0.50% (*w*/*v*)	Treated pears displayed lower counts of mold and yeasts.	[94]

5.2. Stone Fruits

All bioassays cited in this paragraph are reported in Table 5.

Table 5. Overview of antimicrobial activity of EOs, with or without edible coating, in stone fruits.

Fruit	Pathogens	EOs	Coating	EOs Application Method	Reference
Apricots	*Monilinia fructicola* *Botrytis cinerea*	*Thymus vulgaris Eugenia caryophyllata*	-	Spray	[10]
	Alternaria alternata	Syringa EO	-	Inclusion in microcapsules	[95]
		Alpinia officinarum, *Cortex dictamni*, *and Artemisia argyi*	-	Inclusion in microemulsion	[96]
	Aspergillus flavus	*Alpinia officinarum*, *Cortex dictamni*, *and Artemisia argyi*	-	Inclusion in microemulsion	[96]
	Botrytis cinerea	Lemongrass and *Thymus vulgaris*	-	Wound application	[97]
		Syringa vulgaris	-	Inclusion in microcapsules	[95]
		Mint and thyme	Arabic gum 10% and Tween 20	Coating	[98]
	Monilinia laxa	*Alpinia officinarum*, *Cortex dictamni*, and *Artemisia argyi*	-	Inclusion in microemulsion	[96]
		Rosewood EO	-	Vapor-phase and fumigation	[99]
		Thymus vulgaris and verbena	-	Spray	[100]
		Thymus vulgaris and cinnamon	-	Vapor	[101]
		Thymus vulgaris and verbena	-	Spray	[100]
		Thymus vulgaris and savory	-	Biofumigation	[9]
Peaches/nectarines	*M. fructicola*	*Thymus vulgaris*	Chitosan 1.8%-Arabic gum 0.6% (*w*/*v*)	Coating and fumigation	[102]
		Thymus vulgaris	Chitosan 1.8%-Arabic gum 0.6% (*w*/*v*)	Coating	[103]
		Tea tree EO	-	Vapor	[104]
		Aloysia citriodora, *Cymbopogon winterianus*, *Lippia alba*, and *Ocimum americanum* EOs			[105]
	Mucor piriformis	*Alpinia officinarum*, *Cortex dictamni*, and *Artemisia argyi*	-	Inclusion in microemulsion	[96]
		Thymus vulgaris and verbena	-	Spray	[100]
		Rosewood EO	-	Vapor-phase and fumigation	[99]
		Lemongrass and thyme EOs	-	Wound application	[97]
	Penicillium expansum	Mint and thyme EOs	Arabic gum 10% and Tween 20	Coating	[98]
	Rhizopus stolonifer	*Alpinia officinarum*, *Cortex dictamni*, and *Artemisia argyi*	-	Inclusion in microemulsion	[96]
		Rosewood EO	-	Vapor-phase and fumigation	[99]
		Lemongrass and thyme EOs	-	Wound Application	[97]
		Mint and thyme EOs	Arabic gum 10% and Tween 20	Coating	[98]
		Alpinia officinarum, *Cortex dictamni*, and *Artemisia argyi*	-	Inclusion in microemulsion	[96]
		Rosewood EO	-	Vapor-phase and fumigation	[99]
Plums	*Aspergillus flavus* *Aspergillus niger* *Penicillium notatum* *Rhizopus microsporus*	*Allium sativum*	-	Fumigation	[106]

Table 5. *Cont.*

Fruit	Pathogens	EOs	Coating	EOs Application Method	Reference
Sweet cherries	*Aspergillus flavus* *Botrytis cinerea* *Penicillium* (CGMCC 3.13650)	*Zanthoxylum bungeanum*	Polyvinyl alcohol-*β*-Cyclodextrin nanofiber film	Incorporation in nanofibers films	[107]
	Collelotrichum gloeosporioides	Clove	-	Filter paper discs	[108]
	Aspergillus flavus	*Zanthoxylum bungeanum*	Polyvinyl alcohol-*β*-Cyclodextrin nanofibers-film		[107]
		Salvia officinalis, *Zataria multiflora*, and *Cinnamomum zeylanicum*	Chitosan	Dipping	[109] [110]
		Cinnamon		Emulsion and nanoemulsion	[111]
	Botrytis cinerea	*Eucalyptus staigeriana* and *Eucalyptus urograndis*	Carboxymethylcellulose	Dipping	[112]
		Basil	Aloe vera gel coating	Dipping	[113]
		Aloysia citriodora, *Cymbopogon winterianus*, *Lippia alba*, and *Ocimum americanum*			[105]
		Cymbopogon citratus, *Thymus vulgraris*, and *Origanum heracleoticum*		Vapor	[114]
		Eucalyptus camaldulensis, *Mentha piperita*, Moringa oleifera FO		Vapor	[115]
		CT thymol lemongrass, litsea, lavender, peppermint, mint, petitgrain, sage, and thyme			[116]
		Zanthoxylum bungeanum	Polyvinyl alcohol-*β*-Cyclodextrin nanofibers-film		[107]
Strawberries	*Colletotrichum nymphaeae*	*Allium sativum* and *Rosmarinus officinalis*		Vapor	[117]
		Thyme, cinnamon bark, and clove bud		Fumigation	[3]
	C. acutatum	*Aloysia citriodora*, *Cymbopogon winterianus*, *Lippia alba*, and *Ocimum americanum*			[105]
		Eucalyptus staigeriana, *Lippia sidoides*, and *Pimenta pseudocaryophyllus*	Carboxymethylcellulose	Dipping	[118]
	M. fructicola	*Aloysia citriodora*, *Cymbopogon winterianus*, *Lippia alba*, and *Ocimum americanum*			[105]
	Penicillium (CGMCC 3.13650)	*Zanthoxylum bungeanum*	Polyvinyl alcohol-*β*-Cyclodextrin nanofiber film	Incorporation in nanofibers films	[107]
	Rhizopus stolonifer	*Eucalyptus staigeriana*, *Lippia sidoides*, and *Pimenta pseudocaryophyllus*	Carboxymethylcellulose	Dipping	[119]
		Cinnamon		Emulsion and nanoemulsion	[111]
		Eucalyptus staigeriana and *Eucalyptus urograndis*	Carboxymethylcellulose	Dipping	[112]
		Mentha spicata, *Mentha piperita*, *Thymus vulgaris* CT carvacrol, and *Thymus vulgaris* CT thymol		Fumigation	[120]

Monilinia spp. are responsible for brown rots in stone fruits, which are postharvest diseases that cause significant fruit losses [121]. TEO and vervain EO (VEO) showed fungicidal activity against *MFC*, *ML*, and *MFG* in the bioassay on peaches, where a concentration of 1000 ppm and 500 ppm for VEO and TEO, respectively, reduced the brown rot lesion on tested peach fruits [100].

Thyme essential oil is also effective against other postharvest pathogens. In fact, Alamri et al. demonstrated the efficacy of a new coating material to protect peaches against postharvest fungal infections, which contains EOs of mint and thyme (1 mL L^{-1}), gum arabic (10% w/v), and Tween 20. The preparations succeeded in slowing down disease development in vivo and reducing fungal growth in vitro at different temperatures. The fruits were kept in cold storage for up to one month, with very low levels of disease incidence and severity due to the application of the developed materials [98].

Naturally contaminated nectarines and peaches were exposed to TEO and SSEO by biofumigation in order to control postharvest diseases and maintain fruit quality. These EO vapors showed high antifungal activity against *MFC*, reducing fruit rot incidence during shelf-life. In contrast, BC was less sensitive to the treatments with EOs and in vitro tests confirmed the in vivo results. Moreover, EO vapors reduced weight loss and maintained the carotenoid and ascorbic acid content [9]. The effectiveness of the spike lavender, lavender absolute, dill weed, rosewood, FEO, and benchmark TEO against *BC*, *MP*, *PE*, and *RS* was examined in vitro using both the solid-phase diffusion method and the vapor-phase diffusion method, and in vivo on peach fruits. The results of in vitro and in vivo tests

showed that rosewood EO, used in the vapor-phase, prohibited the hypha growth and spore germination of *BC*, *MP*, *PE*, and *RS* at a concentration of 300 µL L^{-1}, keeping the quality of the peach fruit intact [99]. TEO and LgEO inhibited the growth of *BC*, *PE*, and *RS* mycelia by 25 and 50%, respectively, in vitro. Furthermore, the efficacy of a delivery system helps to reduce an unpleasant odor and taste resulting from the use of EOs. The EOs combined with the fungi antagonist *Bacillus amyloliquefaciens* in peach fruits were evaluated. The current investigation showed the potential of adopting *B. amyloliquefaciens* in a biodegradable modified atmosphere (MAP) pad delivery system in conjunction with LgEO to improve the postharvest life of peach fruits and reduce the growth of *BC*, *PE*, and *RS* [97].

Tea tree EO has a strong antifungal activity against *MFC* in vitro and in inoculated peaches. Tea tree EO changes the mycelial morphology, membrane permeability, and levels of intracellular ROS [103]. *O. americanum* and *C. winterianus* acted as antifungals, drastically reducing the growth of *MFC* and *BC* on peach fruits [105].

The use of coating or polysaccharide-based film avoids the problem of the uncontrolled volatilization of EOs and inhibits the growth of bacteria and fungi, allowing for a longer preservation of postharvest fruits [122–125]. Lian et al. [102] tested different chitosan-based films, also adding other polysaccharides, in order to improve the film matrix composition and the antifungal proprieties; specifically, they used films composed of: chitosan 1.8% (*w*/*v*), chitosan 1.2% and xanthan gum 0.6% (*w*/*v*), chitosan 1.8% and pullulan 0.6% (*w*/*v*), chitosan 1.8% and gum tragacanth 0.6% (*w*/*v*), and chitosan 1.8% and Arabic gum 0.6 (*w*/*v*).

The use of thyme essential oil chitosan–Arabic gum composite film on peach fruit by coating or fumigation was the most effective in improving the hydrogen bonding interaction among the film matrix and stabilized the antifungal activity of TEO against *MFC*. Similarly, chitosan–Arabic gum composite films (1.8–0.6% *w*/*v*) with the incorporation of thyme EO reduced the lesion diameter of brown mold caused by *MFC* on the nectarine [103].

Treating 'Spring Princes' and 'Sonnet' peaches with TEO vapor leads to an increase in the total phenolic content and activities of defense-related enzymes and a reduction in brown rot lesion disease [101]. Among 26 EOs, only *M. spicata*, *M. piperita*, TEO *CT carvacrol*, and TEO *CT thymol* exhibited a strong inhibition on *RS* growth in the screening in vitro. Regarding the in vitro results, only peppermint EO (PEO) showed a consistent and substantial effect in limiting lesion growth on peach fruit inoculated with *RS*, whereas all four essential oil treatments reduced disease development [120].

The microcapsules of lilac EO (LLEO) showed strong antifungal activity against *AA* and *BC*, and the peaches' quality attributes were maintained [95].

EOs extracted from galangal (GaEO), cortex EO (CoEO), and artemisia EO (ArEO) showed antifungal activity against pathogens causing postharvest diseases in peaches, such as *PE*, *BC*, *AF*, *AA*, *RS*, and *MFC*. A compound preparation based on the optimized concentration of three EOs was made into a microemulsion and was demonstrated to have greater antifungal activity [96].

The use of TEO and ClEO on apricots had a significant effect on the fruit quality and reduced the incidence and disease severity of *MFC* and *BC*, causal agents of gray and brown mold, respectively [10].

A key factor in fruit storage deterioration is pathogen attack. One of the most significant postharvest pathogens in terms of economic impact is gray mold fungi, which is brought on by *BC* [125].

Chitosan (0.15%) and ZMEO and CEO (0.15%) exhibited antimicrobial power against *BC*. Furthermore, the synergy between chitosan and essential oil (1:1 ratio) also showed antimicrobial power in vitro against *BC*. Similarly, strawberries treated with chitosan, ZMEO, CEO, and their combinations showed a significant reduction in the severity of *BC* compared to control fruits at the end of storage (Figure 4) [110]. Next, the antimicrobial power against *BC* was tested using an *Aloe vera* coating embedded with two different concentrations (500 and 1000 µL L^{-1}) of basil essential oil. After 12 days of cold storage, strawberries treated with *A. vera* and the higher concentration of basil essential oil displayed

the suppression of *BC* mycelium growth in comparison to the control, with no change in the physico-chemical and sensory properties of the fruit [113].

Figure 4. Strawberries fruit treated with chitosan, *Zataria multiflora*, and *Cinnamomum zeylanicum* EOs. Reproduced with permission from Mohammadi, A.; Hashemi, M.; Hosseini, S.M. Innovative Food Science and Emerging Technologies 2015.

Lemon verbena oil (LVEO), LgEO, Pepper–rosemarin oil (PREO), and *Ocimum americanum* EO (OAEO) have shown antifungal activity against *Colletotrichum* sp., BC, and MFC. In vitro tests demonstrated that the use of these EOs with a concentration of 1.2 mL L^{-1} completely constrained CG mycelial growth. LVEO completely stopped BC at a dosage of 0.8 mL L^{-1}, LgEO and PREO at 1 mL L^{-1}, and OAEO at 1.4 mL L^{-1}. LVEO and LgEO prevented the development of *MFC* with a dose of 0.4 mL L^{-1}, PREO at 1.0 mL L^{-1}, and OAEO at 0.8 mL L^{-1}. The four EOs significantly reduced the growth of *Colletotrichum* sp. mycelium on strawberries [105].

PEO and EuEO used in combination (1:1 *v/v*) and the peppermint essential oil completely suppressed the in vitro growth of *BC* mycelium, whereas the EuEO and the Moringa FO coating were less effective. The outcomes of the in vitro tests were confirmed in vivo, with moderate fungus growth when EuEO and Moringa fatty oil were used as treatments, and *BC* was completely inhibited in strawberry samples treated with a combination of PEO and EuEO, or without PEO [115].

Furthermore, sage oil (SaEO) at 1000 µL L^{-1} was able to completely inhibit the growth of *BC* mycelium in vitro. With bioassay studies, it was confirmed that the concentration of 60 µL L^{-1} of SEO was a valid tool for controlling fungal infection, with a low effect on the quality of strawberry fruits [108]. At a concentration of 150 µL L^{-1}, TEO, *Rosalina EO* (RosEO), GaEO, PEO, palmarosa EO (PalEO), LgEO, and OEO completely inhibited *BC*'s mycelial growth, whereas, at a concentration of 100 µL L^{-1}, only LgEO, TEO, and OEO showed complete mycelial inhibition. The in vitro findings reveal that TEO and OEO were particularly effective at preventing postharvest gray mold on strawberry fruit. Exposure to OEO also preserved the fruit quality by preventing the natural deterioration in strawberry [114]. The CEO emulsion and nanoemulsion both exhibited a 100% deterrent percentage in vitro against *BC* at 500 µL L^{-1} and against *RS* at 1000 µL L^{-1}. The fruit

infection rate was lowest (5.43%) in the strawberry fruit treated with CEO nano-emulsion at a concentration of 0.2%; moreover, it had a significant impact on preventing fruit degradation [111]. The in vitro growth of *BC* was fully inhibited by LgEO, litsea EO (LitEO), LEO, PEO, MiEO, LeEO, SaEO, and TEO at a concentration of 625 μL L^{-1}. Strawberry fruits that had been purposefully inoculated with BC, TEO, PEO, LgEO, and LitEO were examined in vivo. At concentrations of 250 or 500 μL L^{-1}, all four EOs exhibited high inhibition; however, at a dose of 125 μL L^{-1}, only PEO was able to prevent the growth of *BC* lesions. However, these EOs changed the sensory quality of strawberries. Nevertheless, LgEO and LitEO EOs seem to be acceptable for consumers when applied at a 125 μL L^{-1} concentration [116].

The name of the disease produced by *RS*, soft rot, already describes the distinctive symptom: a soft, watery rot with juice leakage that, in conditions of high moisture, is covered by mycelium and contains pathogen structures [126]. PEO displayed an antifungal activity on strawberries artificially inoculated with *RS* at 86, 84, and 59% after 24, 48, and 72 h of inoculation, respectively. Furthermore, MiEO, TEO CT carvacrol, and TEO CT thymol also exhibited a fair amount of antifungal power, but much less than PEO [120]. The essential oil of EuEO showed great antifungal capacity in vitro against *BC* and *RS* at concentrations of 2000 and 1500 μL L^{-1}, respectively. In the in vivo strawberry test, EuEO essential oil, when applied curatively in association with carboxymethylcellulose, inhibited the proliferation of *RS* mycelium, whereas it had no antifungal effect against *BC* [112]. On the contrary, Oliveira et al. (2019) [118,119] tested the effectiveness of EuEO, PREO, and PPEO in vitro and in vivo against *RS* and *CA* on strawberry fruits. The PREO presented the highest antifungal activity in vitro ($62.5 < \text{MIC} \leq 125$). In vivo, the EO incorporated in the CMC coating showed efficiency in disease severity reduction in strawberry fruits.

CN is the causative agent of strawberry black spots. Hosseini and coworkers [116] studied the effects of six different concentrations of garlic oil (GEO) (20, 155, 290, 430, 560, and 700 mL L^{-1}) and REO (100, 420, 740, 1060, 1380, and 1700 mL L^{-1}) in vitro and in vivo on strawberry fruit. They argued that GEO and REO significantly inhibited the mycelial growth and conidial germination in vitro of *CN* in contact and vapor assays compared with the untreated control. However, the EC50 assay indicated that GEO was more effective than REO against the pathogen [117]. The results of the in vitro test were confirmed in vivo and in greenhouse conditions; in fact, these EOs significantly reduced the anthracnose disease incidence and severity compared with untreated controls [117].

Collelotrichum gloeosporioids, but, in general, all fungi of this family, is a significant and dangerous saprophytic pathogen of sweet cherries that frequently results in postharvest losses [127]. In vitro tests with TEO, CEO, and ClEO in the contact phase demonstrated the highest inhibitory effect on *CA* mycelial growth at concentrations of 467 and 667 μL L^{-1}, respectively. TEO volatiles totally controlled the disease, whereas CEO volatiles decreased the pathogen penetration and development in strawberry fruit under disease-favorable conditions [3].

Wang and coworkers tested the efficacy of nine EOs (clove, thyme, palmarosa, lemongrass, lemon, cinnamon, and laurel leaf) in vitro in vapor and contact phases (100 and 1000 μL L^{-1}, respectively). Of these, CEO and ClEO showed the greatest inhibition of growth against *CG*. The in vivo findings demonstrated that clove oil was the most effective inhibitor against *CG* in artificially infected sweet cherries. Its fungitoxic activities may be attributed to the destruction of the cell wall and cell membrane, as well as the leakage of intracellular components [108].

Against *AF*, *BC*, and *PE*, Zhang and coworkers [107] tested a new polyvinyl alcohol/β-cyclodextrin (PVA/β-CD, 6:1) nanofibers with ZBEO (10%) incorporated. Both in vitro and in vivo tests on strawberries and sweet cherries showed a significant antifungal activity of film/ZBEO, which increased the shelf-life of fruits, inhibiting the fungi growth without changing their sensory characteristics (Figure 5) [107].

Figure 5. Sweet cherries treated with *Zanthoxylum bungeanum* essential oil incorporated or added to polyvinyl alcohol/*β*-cyclodextrin film. The red circles indicated the presence of fungi. Reproduced with permission from Zhang, H.; Zhang, C.; Wang, X.; Huang, Y.; Xiao, M.; Hu, Y.; Zhang, J. LWT 2022.

The EOs from *Acorus calamus*, *Allium sativum*, *Mucuna pruriens*, and *Sesamum indicum* were particularly successful in in vitro tests in preventing the development of several postharvest fungi. In particular, *PN* was the target of GEO's strongest antifungal action among the EOs tested. GEO also considerably slowed the development of other fungal species that were applied in the test, including *AN*, *AF*, and *RM*. In vivo, the GEO also significantly diminished the growth of *AF* and *AN* on plum fruit, reducing the deterioration of these fruits [106].

Different papers reported antimicrobial effects of EOs on total yeast, molds, and mesophilic bacteria of stone fruit. The antimicrobial activity reported in this review could be analyzed further. The main results of these studies are shown in Table 6.

Table 6. Antimicrobial effect of EOs on microorganisms responsible for fruit spoilage in stone fruits.

Fruit	Pathogen	Coating	EOs	Results	Reference
Apricots	Mesophilic aerobic bacteria and for mold and yeast counts	Basil seed gum 5% Glycerol 30% *w/w* Tween-20 15% Oregano EO (0–6% *v/v*)	Oregano	When increasing OEO concentration, there is an incremental reduction to 31.81% and 25.65% of the total plate counts and yeast and mold counts, respectively	[128]
Sweet cherries	Mesophilic aerobic bacteria	Chitosan 1:3.2 (*w/v*) Tween 80 0.5 wt% pentasodium tripolyphosphate 0.3% (*w/v*)	*Eryngium campestre* EO (800, 1600, 2400, and 3200 mg L^{-1})	Reduction in total bacteria population of around 4 log CFU mL^{-1}	[129]
Strawberries	Total molds, yeast, and mesophilic microorganisms	Aligninate 2% Pectin 2%	Eugenol (0.1–0.2%) Citral (0.15–0.3%)	Decrease in aerobic mesophilic microrganisms, yeasts, and molds development	[130]
		Aloe vera gel (20–40%) Tween 80 (0–01% *w/v*)	Lemongrass 1%	Lower total aerobic mesophilic bacteria and yeast and mold counts	[131]
	Total molds, yeast, and mesophilic microorganisms	Gellan gum (0.5% *w/v*) Glycerol (0.56% *w/v*)	Geraniol 1.2–2.4 µL mL^{-1} Pomegranate extract 360–720 µg mL^{-1}	Psychrophilic bacteria, yeast, mold, and mesophilic bacteria counts were lower and more constant than the control	[132]
		Chitosan and Tween 80	Red thyme, peppermint and limonene	Preservative action on the stored strawberries	[133]
		Gelatin 1:25 (*w/v*) Sorbitol *w/w* Tween 80	Peppermint 0.5–1%	The incorporation of mint EO into gelatin-based edible coating inhibited total aerobic mesophilic flora, molds, and yeasts.	[134]

6. Conclusions and Perspectives

EOs could contribute to the goal of sustainable production because, to date, the acquisition of tolerance by the studied pathogens in treated fresh products has not been

demonstrated. They are considered safe for both the environment and human health, so interest in their use as antimicrobial agents for fresh produce has increased in recent years. Several research studies have been conducted to demonstrate the benefits of EOs in containing many fruit postharvest diseases. In general, EOs extracted from different plant organs have been found to be non-harmful to fresh food, human health, and the environment if the correct doses and timing are observed.

Several research studies have been conducted under in vitro conditions. Research on the use of EOs on fresh fruit has shown that the EOs concentration and their compounds, required to inhibit microbial growth, are generally higher in food than in culture media. Unfortunately, in some cases, the concentrations that are effective against the disease can be phytotoxic and cause the further chemical deterioration of treated food.

Botanicals can be applied in the form of dipping, but several studies report their use as vapors due to their advantage in preventing product contamination. Many of these EOs have already been registered as flavoring agents, so they can easily be registered for postharvest use. Despite all of the obvious advantages, much work remains to be carried out on the detailed examination of the biological activity and dispersion of EOs and their compounds in fruit tissues in order to develop a formulation that maintains antimicrobial activity without causing undesirable effects on the foods. A viable alternative to increasing the half-life of the EOs and reducing the contact between the essential oil and the food, so as to reduce the possibility of undesirable effects on the fruit, is the inclusion of the EOs in nanoparticles, coatings, or films.

The inclusion of EOs in film, coating, and/or nanoparticles represents a valid strategy for increasing the water solubility, stability, and bioavailability and decreasing the volatility of EOs. To date, there are few scientific contributions reporting the active inclusion of EOs as a treatment against postharvest pathogens in fruits of the *Rosaceae* family.

Author Contributions: Conceptualization, A.M.; investigation, A.M. and M.C.; resources, A.M. and M.C.; data curation, A.M.; writing—original draft preparation, A.M. and M.C.; writing—review and editing, A.M., V.B., A.F. and M.P.; visualization, A.F. and M.P.; supervision, A.F. and M.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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