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REVIEW ARTICLE

Current status of the effectiveness of essential oils for controlling phytopathogenic fungi, a review

Estado actual de la efectividad de aceites esenciales para el control de hongos fitopatógenos, una revisión

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ABSTRACT

Essential oils (EOs) are volatile plant derivatives that have been evaluated in the control of phytopathogenic fungi, and whose effectiveness has been associated with the part of the plant and concentration used. Hereby we provide an overview of the role of EOs on phytopathogenic fungi agents, presenting an overview of its diversity, constituents, tests under *in vivo* and *in vitro* conditions, their mechanisms of action, and the techniques to assess its effectiveness. The antimicrobial action of EOs is attributed to their ability to penetrate through cell membranes and inhibit the functional properties of fungal cells.

KEYWORDS

Hydrodistillation, secondary metabolites, *in vitro* and *in vivo* studies, direct contact and vapor phase techniques, coatings and bioactive films.

RESUMEN

Los aceites esenciales (AEs) son derivados volátiles de plantas que han sido evaluados en el control de hongos fitopatógenos y su efectividad se ha asociado con la parte de la planta y la concentración utilizada. Aquí presentamos una revisión del papel de los AEs en el control de hongos fitopatógenos, con una panorámica de su diversidad, constituyentes, pruebas bajo condiciones *in vivo* e *in vitro*, sus mecanismos de acción y las técnicas para evaluar su efectividad. La acción antimicrobiana de los AEs se atribuye a su capacidad para penetrar las membranas celulares e inhibir las propiedades funcionales de las células fúngicas.

PALABRAS CLAVE

Hidrodestilación, metabolitos secundarios, estudios *in vitro* e *in vivo*, técnicas de contacto directo y fase de vapor, recubrimientos y películas bioactivas

Introduction

Phytopathogenic fungi are responsible for diseases in a large number of vegetable and fruit products, which may appear during crop development or postharvest (Mamgain et al. 2013). There are several methods considered to minimize losses and maintain the quality and safety of the horticultural product, being the application of chemical treatments one of the most widely used (Ruiz et al. 2012). Still, mismanagement and the presence of residues cause human health to be affected as well as resistant strains to be generated (McCarroll et al. 2002).

The purpose of the present review is to present an in-depth analysis of the information that is available on the aforementioned subject, to position the use and effectiveness of Essential oils (EOs) as a state-of-the-art alternative to control phytopathogenic fungi. In this study, EOs from 54 plant species were found to exhibit a potential role as a fungicide on 60 different fungal species. Also, this information will serve as the basis for selecting the most effective EOs for future applications into biodegradable systems in various horticultural commodities.

EOs are volatile plant derivatives (Franz and Novak 2009; Krisch et al. 2011), which are responsible for their aroma. In the plant, they serve several purposes: as messengers, attractors of pollinators, and as a defense against herbivores and microorganisms that cause diseases. This last characteristic is what confers its properties as an agent for the control of phytopathogenic fungi (Baser and Buchbauer 2009; Kubeczka 2009).

Since the Middle Ages, EOs have been used by man, not only as flavor and food preservatives, but also as cosmetics, aphrodisiacs, and medicine (Dima and Dima 2015; Mandal and Mandal 2015), as well as for the protection and control of pests and diseases in stored grains (Isman 2000). For example, a study published in 1880 describes the activity of cinnamon essential oil for the control of anthrax bacilli (Kocić-Tanackov and Dimić 2013).

Currently, there are about 2,000 species of plants from which EOs have been obtained, and around 300 of them are commercially available (Raut and Karuppayil 2014). The EOs can be obtained from various parts of the plant (Krisch et al. 2011). For example, from the aerial part, chia (*Salvia hispanica* L.) (Elshafie et al. 2018), mint (*Mentha spicata* L.) (Kedia et al. 2015), and rue (*Ruta graveolens* L.) (Haddouchi et al. 2013); from leaves, basil (*Ocimum selloi* Benth.) (Costa et al. 2015), and orange (*Citrus sinensis* (L.) Osbeck.) (Hamdani and Allem 2015); from flowers, chamomile (*Matricaria chamomilla* L.) (Lu et al. 2013), and gypsy grass (*Bupleurum falcatum* L.) (Mohammadi et al. 2014); from bark, cinnamon (*Cinnamomum zeylanicum* Blume.) (Black-Solis et al. 2017); from the root, santolina (*Santolina chamaecyparissus* L.) (Salah-Fatnassi et al. 2017); from the rhizome, white ginger (*Hedychium coronarium* J. Koenig.) (Ray et al. 2018); from fruits, hemlock (*Cicuta virosa* var. *latisecta* Čelak.) (Tian et al. 2011a), and from seeds, dill (*Anethum graveolens* L.) (Ma et al. 2015a) and cumin (*Cuminum cyminum* L.) (Kedia et al. 2014b).

Conventionally, EOs can be obtained by two processes: cold pressure and distillation. There are several methods in connection to the latter, like hydrodistillation, and steam distillation (which can be used with high pressure) (Kubeczka 2009). EOs can also be obtained through other methods, like extraction with organic solvents, with liquid carbon dioxide, with supercritical fluids, and with microwaves (Ma et al. 2015b; Mansoreh et al. 2015; Pavlić et al. 2015; Torrenegra et al. 2015).

The content of components and the effectiveness of EOs in the control of phytopathogenic fungi depend on several factors, including the part of the plant used to obtain the EO, its concentration, as well as the environmental conditions and stress to which the botanical species was subjected during their development (Schmidt 2009), among other factors.

Constituent components of EOs

Plants produce a series of secondary metabolites (more than 100,000 identified) classified into nitrogen-free compounds (terpenes, polyketides, phenolics, saponins, and polyacetylenes), and nitrogen-containing compounds (alkaloids, amines, cyanogenic glycosides, non-protein amino acids, glucosinolates, alkamides, and peptides) (Wink 2010).

Many components that constitute EOs and which are mixtures of low molecular weight compounds (between 85 and 99%) are volatile.

The main constituents are derived from three routes of biosynthesis: the mono and diterpenes from the methyl-erythritol pathway, the sesquiterpenes from the mevalonate pathway, and the phenylpropenes from the shikimic acid pathway (Franz and Novak 2009).

Terpenes are the combinations of isoprene molecules (5 carbon unit -C5), monoterpenes (C10), diterpenes (C20), and sesquiterpenes (C15). Terpenoids are terpenes that contain oxygen in their structure. Phenylpropane derivatives are aromatic compounds, such as aldehydes (citral), alcohols (geraniol), and phenols (thymol) (Sánchez-González et al. 2011).

In almost all the studies carried out, the identification and quantification of the constitutive components of EOs were made utilizing the gas chromatography technique coupled to mass spectrometry (GC-MS). Another method which is used with a lower frequency is the thin layer chromatography (Gemeda et al. 2015).

An EO can be constituted by more than 100 different components and in differing proportions, which can vary depending on the effect of the species (Dima and Dima 2015). There are plant species in which the main component amounted to more than 80% of the EO (Table 1). For example, in spice cloves (*Eugenia caryophyllus*, Spreng) (Bullock & S.G.Harrison), eugenol represents 90.5% (Castro et al. 2017); for basil (*O. selloi*), methyl chavicol constitutes 93.2% of the total (Costa et al. 2015); in orange (*C. sinensis*), DL-limonene, 90.6% (Singh et al. 2010); in pulicaria (*Pulicaria mauritanica* Batt.), carvotanacetone, 87.3% (Znini et al. 2013); in oregano (*Origanum vulgare* L.), carvacrol, 86.9% (Zabka et al. 2014); in mountain rue (*Ruta angustifolia* Pers.), 2-undecanone, 82.4% (Haddouchi et al. 2013); in clove (*Syzygium aromaticum* (L.) Merr. & L.M.Perry.), eugenol, 82.3% (Manganyi et al. 2015), and in cinnamon (*C. zeylanicum*) trans-cinnamaldehyde represented 80.4% (Lu et al. 2013).

Table 1. Plant species, main compounds identified and relative percentage, of EOs used for *in vitro* and *in vivo* evaluations against phytopathogenic fungi.

Plant species	EO main compounds	Relative percentage	Reference
Solidago canadensis L.	Germacrene D, limonene	34.9, 12.5	Elshafie et al. 2019
Helichrysum microphyllum subsp. *tyrrhenicum* Bacch. & al.	Neryl acetate, c-curcumene, farnesene, 5-eudesmen-11-ol	33.6, 11.5, 7.3, 4.3	Juliano et al. 2019
Salvia officinalis L.	1.8-Cineole, α-thujone, camphor	14.6, 20.6, 19.3	Rguez et al. 2019
Rabdosia rugosus Wall. (Syn. *Plectranthus rugosus* Wall.)	α-bisabolol	41.9	Singh et al. 2019
Salvia hispanica L.	(Z)-caryophyllene, (E)-caryophyllene	11.5, 10.6	Elshafie et al. 2018
Hedychium coronarium J. Koenig.	β-pinene, eucalyptol, linalool, coronarin-E, α-pinene, ϱ-cymene	12.7-42.7, 7.3-42.2, 1.9-45.1, 1.0-39.5, 3.8-16.6, 1.2-13.3	Ray et al. 2018
Melaleuca alternifolia (Maiden & Betche) Cheel.	Terpinene-4-ol, γ-terpinene, α-terpinene	31.1, 25.3, 12.7	Zhang et al. 2018
Cinnamomum zeylanicum Blume.	Eugenol	80.0	Castro et al. 2017
Cymbopogon flexuosus (Nees ex Steud.) W.Watson.	E-Caryophyllene, geranial, geraniol, neral	21.4, 15.3, 14.5, 14.1	
Eucalyptus globulus Labill.	1,8-cineole	78.9	
Eugenia caryophyllus (Spreng.) Bullock & S.G.Harrison.	Eugenol	90.5	
Rosmarinus officinalis L.	α-pinene, 1,8-cineole, camphor	24.5, 19.4, 22.0	
Helichrysum italicum (Roth) G.Don.	α-cedrene, α-curcumene, geranyl acetate	13.6, 11.4, 10.0	Djihane et al. 2017

Plant species	EO main compounds	Relative percentage	Reference
Ocimum selloi Benth.	Methyl chavicol	93.2	Costa et al. 2015
Trachyspermum copticum (L.) Link. (Syn. *Trachyspermum ammi* (L.) Sprague.)	Thymol, ρ-cimene, γ-terpinene	29.6, 16.0, 17.8	Khosravi et al. 2015
Anethum graveolens L.	Limonene, carvone, apiol	32.6, 41.5, 16.7	Ma et al. 2015a
Thymus vulgaris L. *Lippia rehmannii* H.Pearson. *Syzygium aromaticum* (L.) Merr. & L.M.Perry. *Cinnamomum zeylanicum*	Thymol, terpinen-4-ol Geranial, neral Eugenol, β-Caryophyllene Eugenol	45.2, 12.3 34.5, 20.2 82.3, 11.0 12.8	Manganyi et al. 2015
Thymus vulgaris *Pelargonium odoratissimum* (L.) L'Hér.	ρ-cimene, thymol β-citronellol, geraniol	21.9, 44.6 24.8, 12.5	Matusinsky et al. 2015
Thymus vulgaris *Cinnamomum cassia* L.	Thymol, ρ-cimene, γ-terpinene Cinnamaldehyde, cinnamyl acetate	35.6, 19.5, 10.5 73.6, 3 - 15	Pekmezovic et al. 2015
Anthemis odontostephana Boiss. Var. *odontostephana*	Flower: borneol, (-)-bornyl acetate Leaf: borneol, myristicin Stem: borneol, myristicin	Flor: 31.3, 13.9 Hoja: 19.2, 13.3 Tallo: 27.0, 11.2	Zebarjad and Farjam 2015
Artemisia monosperma Delile.	Capylene, capilin, γ-terpinene	36.8, 14.6, 12.4	Badawy and Abdelgaleil 2014
Cymbopogon nardus (L.) Rendle.	Citronellal, citronellol, geraniol	26.2, 12.9, 19.7	Chen et al. 2014
Mentha spicata L.	DL-Limonene, dextro-carvone	25.5, 59.6	Kedia et al. 2014a
Cuminum cyminum L.	Laevo β-pinene, cimeno, γ-terpinene, cuminaldehyde	11.5, 47.0, 19.3,14.9	Kedia et al. 2014b
Thymus kotschyanus Boiss. & Hohen. *Thymus daenensis* Celak. *Stachys pubescens* Ten. *Bupleurum falcatum* L.	Thymol α-terpineol, thymol, carvacrol 2,6-octadiene, δ-cadinene, germacrene Torilenol, spatulenol	46.7 22.9, 20.2, 31.4 11.5, 19.7, 22.4 39.1, 19.6	Mohammadi et al. 2014
Satureja hortensis L. *Origanum heracleoticum* L. *Thymus vulgaris* *Rosa × damascena* Herrm. *Pelargonium graveolens* L'Hér. *Melaleuca alternifolia*	Carvacrol, ρ-cimene Carvacrol Thymol, ρ-cimene Citronellol, geraniol Citronellol, geraniol Terpinen-4-ol, γ-terpinene	50.0, 12.2 75.8 43.7, 23.2 51.3, 25.8 39.0, 11.3 40.7, 17.8	Stević et al. 2014
Laurus nobilis L.	Cinnamaldehyde, eugenol	30.2, 44.1	Xu et al. 2014
Carum carvi L. *Coriandrum sativum* L. *Mentha arvensis* L. *Ocimum citriodorum* Vis. *Origanum vulgare* L. *Pimenta racemosa* (Mill.) J.W.Moore. *Thymus satureoides* Coss. & Balansa. *Thymus vulgaris*	Carvone, limonene Linalool Menthol, menthon, isomenthon Geranial, neral, linalool Carvacrol Eugenol, myrcen Borneol, thymol, carvacrol Thymol, ρ-cimene	68.7, 21.5 66.7 42.1, 21.7, 13.6 31.1, 23.6, 16.4 86.9 64.0, 14.6 29.8, 12.0, 10.0 60.2, 19.9	Zabka et al. 2014

Plant species	EO main compounds	Relative percentage	Reference
Ruta angustifolia Pers.	2-decanone, 2-undecanone	10.0, 82.4	Haddouchi et al. 2013
Ruta chalepensis var. *bracteosa* (DC.) Boiss.	2-nonanone, 1-nonene, 2-undecanone	32.7, 13.9, 32.5 21.6, 55.4	
Ruta graveolens L.	2-nonanone, 2-undecanone		
Cinnamomum zeylanicum	3-phenylpropionaldehyde, *trans*-cinnamaldehyde	10.4, 80.4	Lu et al. 2013
Pelargonium graveolens	Citronellol, citronellyl formate	41.5, 10.8	
Cuminum cyminum	β-pinene, ρ-cymene, γ-terpinene, cuminaldehyde ρ-cimene, thymol	14.0, 16.8, 11.3, 46.9	
Thymus vulgaris	Linalool, methyl chavicol	37.6, 39.7	
Ocimum basilicum L.	Citronellal, citronellol,	45.9, 35.0	
Cymbopogon citratus (DC.) Stapf.	geranial	20.7, 14.1, 26.0	
Melaleuca alternifolia	Terpinen-4-ol	50.2	Shao et al. 2013
Pulicaria mauritanica Batt.	Carvotanacetone	87.3	Znini et al. 2013
Eucalyptus tereticornis Sm.	α-pinene, β-pinene, 1,8-cineole	22.5, 22.5, 19.8	Guleria et al. 2012
Armoracia rusticana P.Gaertn., B.Mey. & Scherb.	Allyl isothiocyanate, β-phenylethyl isothiocyanate	63.7, 23.9	Kloucek et al. 2012
	Diallyl disulfide, diallyl trisulfide	43.8, 27.1 79.3	
Allium sativum L.	trans-cinnamaldehyde	28.4, 20.2, 17.9	
Cinnamomum aromaticum Nees.	Carvacrol, thymol, ρ-cimene		
Origanum compactum Benth.			
Zataria multiflora Boiss.	Carvacrol	76.1	Mahmoudi et al. 2012
Cicuta virosa var. *latisecta* Celak.	ρ-cimene, γ-terpinene, cuminaldehyde	27.9, 40.9, 21.2	Tian et al. 2011a
Thymus vulgaris	γ-terpinene, ρ-cimene	17.1, 14.6	Bosquez-Molina et al. 2010
Citrus aurantifolia (Christm.) Swingle.	D-Limonene, β-pinene, γ-terpinene	45.1, 20.5, 10.5	
Verbena officinalis L.	Isobornyl formate, (E)-citral	45.4, 44.5	Camele et al. 2010
Thymus vulgaris	o-cimene, carvacrol	56.2, 24.4	
Origanum vulgare	o-cimene, carvacrol	41.9, 44.0	
Citrus maxima (Burm.) Merr.	DL-Limonene, 1-hexene, 4-Methy, Z-citral, *E*-citral	31.8, 15.2, 13.3, 17.7	Singh et al. 2010
Citrus sinensis (L.) Osbeck.	DL-Limonene	90.66	

Some compounds are present in several plant species in different concentrations. For example, carvacrol is present in four species: oregano (*O. vulgare*), 44.0% (Camele et al. 2010); Zataria (*Zataria multiflora* Boiss.), 76.1% (Mahmoudi et al. 2012); summer savory (*Satureja hortensis* L.), 50.0% (Stević et al. 2014), and avishan-e-denaii (*Thymus daenensis* Celak.), 31.4% (Mohammadi et al. 2014); eugenol, in four species: clove (*S. aromaticum*), 82.3%; cinnamon (*C. zeylanicum*), 12.8% (Manganyi et al. 2015); sweet bay (*Laurus nobilis* L.), 44.1% (Xu et al. 2014); and bay rum tree (*Pimenta racemosa* (Mill.) J.W.Moore.), 64.0% (Zabka et al. 2014); the geranial in three species: lipidia (*Lippia rehmannii* H.Pearson.), 34.5% (Manganyi et al. 2015); basil sweet-lemon (*Ocimum citriodorum* Vis.), 31.1% (Zabka et al. 2014), and lemongrass (*Cymbopogon citratus* (DC.) Stapf.), 26.0% (Lu et al. 2013); finally, linalool, in two species: coriander (*Coriandrum sativum* L.), 66.7% (Zabka et al. 2014), and sweet basil (*Ocimum basilicum* L.), 45.9% (Lu et al. 2013). These compounds

are secondary metabolites that occur in some plant species and serve as a defense against microorganisms. According to Sell (2009), few of them share the same biosynthetic pathways.

In other cases, the same component can vary in concentration between species of the same genus. The 2-undecanone level is 82.4% in mountain rue (*R. angustifolia*), 55.4% in rue (*R. graveolens*), and 32.5% in fringed rue (*Ruta chalepensis* var. *bracteosa* [DC.] Boiss.) (Haddouchi et al. 2013). Carvacrol represents 86.9% in oregano (*O. vulgare*) (Zabka et al. 2014), 75.8% in oregano (*O. heracleoticum* L.) (Stević et al. 2014), and 28.4% in sahtar (*O. compactum* Benth.) (Kloucek et al. 2012), whereas thymol can be quantified as 60.2% in thyme (*T. vulgaris* L.) (Zabka et al. 2014), but it can be 46.7% in other species such as *T. kotschyanus* Boiss. & Hohen. (Mohammadi et al. 2014).

There are also variations in the concentration of the same compound in the same species, for example, thymol in *T. vulgaris*, with 35.6 to 60.2% (Pekmezovic et al. 2015; Zabka et al. 2014), carvacrol in *O. vulgare*, 44.0 to 86.9% (Camele et al. 2010; Zabka et al. 2014), and terpinen-4-ol in tea tree (*Melaleuca alternifolia* [Maiden & Betche] Cheel.), with 31.1 to 50.2% (Shao et al. 2013; Stević et al. 2014; Zhang et al. 2018). According to Schmidt (2009), the content of EOs components may depend on several factors, including the organ of the plant used, environmental conditions, and the stress to which the botanical species was subjected during its development in the field.

Potential of Eos for controlling phytopathogenic fungi

EOs have been tested for the control of phytopathogenic fungi in *in vitro* and *in vivo* studies. The literature reports that the effectiveness of EOs varied depending on the plant species, microorganism, EO concentration, and the evaluation technique used, among other factors.

Techniques to evaluate the effectiveness of the EOs on fungal development

Two techniques are used to evaluate the effectiveness of EOs. The first is through direct contact, in which case, the EO is mixed with the culture medium, either solid or liquid (*in vitro* studies), or placed directly on the fruit (*in vivo* studies). The second is through vapor phase, where the EO is impregnated in an absorbent element, and then it is volatilized flooding the environment where the fungus has been placed (Petri dish for *in vitro* studies and hermetic containers for *in vivo* studies).

Thus, the same technique can have different names. When it involves direct contact in the solid medium it is known as toxic medium assay (Manganyi et al. 2015), poisoned medium technique (Chen et al. 2014), dilution in agar method (Hamdani and Allem 2015), radial growth inhibition technique (Badawy and Abdelgaleil 2014), and agar well diffusion method (Ray et al. 2018). Other methods reported *in vitro* are direct contact in the liquid medium, micro, and macro dilution in broth (Juliano et al. 2019; Khosravi et al. 2015; Martins et al. 2013), and in the vapor phase, disc diffusion (Kloucek et al. 2012; Rguez et al. 2019; Zhang et al. 2018), drop diffusion test (Saroj et al. 2015), and soaked cotton (Mahmoudi et al. 2012).

In *in vivo* studies, the following techniques have been reported: by direct contact and aspersion (Camele et al. 2010), by immersion (Bosquez-Molina et al. 2010), in the vapor phase, soaked cotton (Kedia et al. 2014b), sterile paper discs (Stević et al. 2014), and drop (Mehra et al. 2013).

To evaluate the effectiveness of EOs, we used the minimum inhibitory concentration (MIC), which is defined as the lowest EO concentration that completely inhibits the growth of the phytopathogenic fungus —a synonym used for this is 'the minimum inhibitory amount' (MIA) (Guleria et al. 2012, Van de Vel et al. 2019). The minimum fungicidal concentration (MFC), defined as the lowest concentration, resulted in zero fungus growth when it is cultivated again in a culture medium —and a synonym for it could be 'the minimum lethal concentration' (MLC) (Martins et al. 2013).

EOs in the control of phytopathogenic fungi *in vitro*

Table 2 presents a series of studies in which EOs obtained from 54 plant species were effective in controlling 60 species of phytopathogenic fungi. The genera with the highest number of species were: *Citrus* (Bosquez-Molina et al. 2010; Dimić et al. 2014;

Singh et al. 2010), and *Ruta*, both from the Rutaceae family (Haddouchi et al. 2013) with four species each, the genera *Cinnamomum* (Lauraceae family) (Kloucek et al. 2012; Manganyi et al. 2015; Pekmezovic et al. 2015), *Ocimum* (Costa et al. 2015; Lu et al. 2013; Zabka et al. 2014), and *Thymus* (Lamiaceae family) (Camele et al. 2010; Mohammadi et al. 2014; Zabka et al. 2014), with three species each, and the genera *Pelargonium* (Geraniaceae family) (Lu et al. 2013; Matusinsky et al. 2015), *Mentha* (Kedia et al. 2014a; Lu et al. 2013), *Origanum* (Lamiaceae family) (Stević et al. 2014; Zabka et al. 2014), *Helichrysum* (Asteraceae family) (Juliano et al. 2019; Ray et al. 2018), and *Salvia* (Lamiaceae family) (Elshafie et al. 2018; Rguez et al. 2019), with two species each.

Botanical species with the greatest capacity reported for *in vitro* fungi control were dill (*Apium graveolens* L.) against *Sclerotinia sclerotiorum* (Lib.) de Bary. in 0.12 μL mL^{-1} doses (Ma et al. 2015a); oregano (*O. vulgare*) against *Aspergillus flavus* Link., and *A. niger* P.E.L. van Tieghem. (de Sousa et al. 2013), and verbena (*Verbena officinalis* L.), thyme (*T. vulgaris*), and oregano (*O. vulgare*) for *Botrytis cinerea* Pers., *Penicillium italicum* Wehmer., and *Phytophthora citrophthora* R.&E. Sm. Control (0.25 μL mL^{-1}) (Camele et al. 2010).

They are followed by tea tree EOs (*M. alternifolia*) against *B. cinerea*, 0.4 μL mL^{-1} dose (Shao et al. 2013), basil (*O. selloi*) against *Moniliophthora perniciosa* (Stahel) Aime & Phillips-Mora. (Costa et al. 2015), thyme (*T. vulgaris*), clove (*S. aromaticum*), and cinnamon (*C. zeylanicum*) against *Fusarium oxysporum* Schlecht. (Manganyi et al. 2015), and everlasting (*Helichrysum splendidum* [Thunb.] Less.) against *Colletotrichum gloeosporioides* (Penz.) Penz. & Sacc. in 0.5 μL mL^{-1} doses (Mashigo et al. 2015). The EO of cumin (*C. cyminum*) against *A. flavus*, 0.6 μL mL^{-1} doses (Kedia et al. 2014b), grapefruit (*Citrus maxima* (Burm.) Merr.), and orange (*C. sinensis*) against the same microorganism in 0.75 μL mL^{-1} doses (Singh et al. 2010), and Mexican lemon (*C. aurantifolia* (Christm.) Swingle.), and thyme (*T. vulgaris*) against *C. gloeosporioides* in 0.85 μL mL^{-1} doses (Bosquez-Molina et al. 2010).

Finally, effective EOs that are reported at concentrations of less than 1 μL mL^{-1} were peppermint (*M. spicata*) against *A. flavus* (Kedia et al. 2014a), rosemary (*Rosmarinus officinalis* L.) against *A. flavus* and *A. niger* (de Sousa et al. 2013), mint geranium (*Pelargonium odoratissimum* (L.) L'Hér.), and thyme (*T. vulgaris*) against *Oculimacula yallundae* (Walker & Spooner) Crous & Gams., *Zymoseptoria tritici* (Desm.) Quaedvlieg & Crous., and *Pyrenophora teres* Drechsler. (Matusinsky et al. 2015), and caraway (*Carum carvi* L.), lemon basil (*O. citriodorum*), oregano (*O. vulgare*), malagueta (*P. tolonif*), Moroccan thyme (*Thymus satureoides* Coss. & Balansa.), and thyme (*T. vulgaris*) against *A. niger*, *Cladosporium cladosporioides* (Fresen.) G.A. de Vries., and *Stachybotrys chartarum* (Ehrenb.) S. Hughes. (Zabka et al. 2014).

EOs in the control of phytopathogenic fungi *in vivo*

Overall, the reported EO with the lowest effective dose (0.50 μL mL^{-1}) was dill (*A. graveolens*) for the control of white rot (*S. sclerotiorum*) in artificially inoculated leaves of turnip (*Brassica napus* L.). When the EO was sprayed before inoculation, the development of the pathogen was inhibited. At the same time, in the control treatment, lesions reached up to 30.2 mm in diameter (Ma et al. 2015a) (Table 2).

In the vapor phase, the cumin EO (*C. cyminum*) with a 0.6 μL mL-1 dose, for the control of *A. flavus* in wheat seeds (*Triticum aestivum* L.) and chickpea (*Cicer arietinum* L.), with about 65.1% and 50.0%, respectively after 12 months of storage (Kedia et al. 2014b). Likewise, *A. flavus* and *A. niger* fungi of the table grapes (*Vitis labrusca* L.) were inhibited for 12 and 24 days, by immersion in rosemary EO (*R. officinalis*) at 1 μL mL^{-1} concentration when stored at room temperature (25°C) and 12°C, respectively (de Sousa et al. 2013).

In papaya fruit (*Carica papaya* L.), thyme EO (*T. vulgaris*) was effective for the control of anthracnose disease (*C. gloeosporioides*) employing an immersion treatment of 1.5 μL mL^{-1}. When the EO was applied after inoculation, the inhibition was 100%. In contrast, if the treatment was applied after inoculation, a 50% inhibition was achieved (Bosquez-Molina et al. 2010).

The application by sprinkling of 2 μL mL^{-1} of thyme EO (*T. vulgaris*) in orange fruits (*C. sinensis*) for controlling gray mold (*B. cinerea*), phytophthora (*P. citrophthora*), and rhizopus rot (*Rhizopus tolonifera* (Ehrenb.) Vuill.) was 100% effective (Camele et al. 2010).

Table 2. Plant species and EOs doses applied for *in vitro* and *in vivo* control of various phytopathogenic fungi.

Plant species	Phytopathogenic fungi	Evaluation	EO dose	Reference
Solidago canadensis	*Monilinia fructicola* (G. Winter) Honey.	*In vitro*	1000 μg mL^{-1}	Elshafie et al. 2019
Helichrysum microphyllum subsp. *tyrrhenicum*	*Aspergillus brasiliensis* Varga, Frisvad & Samson	*In vitro*	2.00 mg mL^{-1}	Juliano et al. 2019
Salvia officinalis	*Botrytis cinerea* Pers., *Fusarium sambucinum* Fuckel.	*In vitro*	1.93 μg mL^{-1}	Rguez et al. 2019
Rabdosia rugosus	*Rhizoctonia solani* J.G. Kühn., *Sclerotium rolfsii* Sacc., *Fusarium oxysporum* Schlecht.	*In vitro*	250 ppm	Singh et al. 2019
Salvia hispanica	*Monilinia laxa* (Aderh. y Ruhl.), *M. fructicola*, *M. fructigena* (Aderh. & Ruhland) Honey., *Aspergillus fumigatus* Fresen., *Penicillium digitatum* (Pers.) Sacc., *P. expansum* Link.	*In vitro*	40%	Elshafie et al. 2018
Hedychium coronarium	*Aspergillus niger* P.E.L., *A. flavus* Link., *Fusarium oxysporum*	*In vitro*	6.25 μg mL^{-1}	Ray et al. 2018
Melaleuca alternifolia	*Penicillium italicum* Wehmer., *P. digitatum*	*In vitro*	12 mg mL^{-1}	Zhang et al. 2018
Helichrysum italicum	*Fusarium solani* var. *coeruleum* (Lib. ex Sacc.) C. Booth., *Aspergillus niger*, *Ascochyta rabiei* (Pass.) Labr.	*In vitro*	50.6 μg mL^{-1}	Djihane et al. 2017
Ocimum selloi	*Moniliophthora perniciosa* (Stahel) Aime & Phillips-Mora.	*In vitro*	500 ppm	Costa et al. 2015
Lippia adoensis var. *koseret* Sebsebe.	*Aspergillus flavus*, *A. parasiticus* Speare., *A. niger*, *A. fumigatus*	*In vitro*	2 μL mL^{-1}	Gemeda et al. 2015
Anethum graveolens	*Sclerotinia sclerotiorum* (Lib.) de Bary.	*In vitro* *In vivo* (turnip)	Medium - 1.0 μL mL^{-1} Air - 0.125 μL mL^{-1} 0.50 μL mL^{-1}	Ma et al. 2015a
Thymus vulgaris *Syzigium aromaticum* *Cinnamomum zeylanicum*	*Fusarium oxysporum*	*In vitro*	500 μL L^{-1}	Manganyi et al. 2015
Helichrysum splendidum (Thunb.) Less.	*Colletotrichum gloeosporioides* (Penz.) Penz. & Sacc.	*In vitro*	500 μL L^{-1}	Mashigo et al. 2015
Thymus vulgaris *Pelargonium odoratissimum*	*Oculimacula yallundae* (Walker & Spooner) Crous & Gams. (Desm.) Quaedvlieg & Crous. *Pyrenophora teres* Drechsler.	*In vitro*	1.0 μL mL^{-1}	Matusinsky et al. 2015
Thymus vulgaris *Cinnamomum cassia*	*Aspergillus flavus*	*In vitro*	31.2 μg mL^{-1} 62.5 μg mL^{-1}	Pekmezovic et al. 2015
Anthemis odontostephana var. *odontostephana*	*Aspergillus niger* *Fusarium solani* (Mart.) Sacc.	*In vitro*	32.6 μg mL^{-1}	Zebarjad and Farjam 2015

Plant species	Phytopathogenic fungi	Evaluation	EO dose	Reference
Citrus limon (L.) Osbeck.	*Aspergillus parasiticus*, *A. carbonarius* (Bainier) Thom. *Cladosporium cladosporioides* (Fresen.) G.A. de Vries. *Eurotium herbariorum* (F.H. Wigg.) Link. *Penicillium chrysogenum* Thom.	*In vitro*	2.5 μL mL^{-1}	Dimić et al. 2014
Mentha spicata	*Absidia ramosa* (Zopf) Lendn. *Aspergillus flavus*, *A. fumigatus*, *A. glaucus* (L.) Link., *A. niger*, *A. unguis* (Émile-Weill & L. Gaudin) Dodge. *Cladosporium cladosporioides* *Curvularia lunata* (Wakker) Boedijn. *Fusarium oxysporum* *Mycelia sterilia* *Penicillium citrinum* Thom., *P. italicum*, *P. luteum* Zukal., *P. purpurogenum* Stoll. *Rhizopus stolonifer* (Ehrenb.) Vuill. *Spondylocladium australe* J.C. Gilman & E.V. Abbott.	*In vitro*	1.0 μL mL^{-1}	Kedia et al. 2014a
Cuminum cyminum	*Absidia ramosa* *Aspergillus flavus*, *A. fumigatus*, *A. glaucus*, *A. niger*, *A. unguis* *Cladosporium cladosporioides* *Curvularia lunata* *Fusarium oxysporum* *Mycelia sterilia* *Penicillium citrinum*, *P. italicum*, *P. luteum*, *P. purpurogenum* *Rhizopus stolonifer* *Spondylocladium australe*	*In vitro* *In vivo* (wheat and chickpea)	0.6 μL mL^{-1}	Kedia et al. 2014b
Thymus kotschyanus *Stachys pubescens*	*Fusarium oxysporum* *Aspergillus flavus*	*In vitro*	0.5 μg mL^{-1}	Mohammadi et al. 2014
Pinus nigra subsp. pallasiana (Lamb.) Holmboe. *Pinus nigra* var. *banatica* Georgescu & Ionescu	*Aspergillus niger*	*In vitro*	5 mg mL^{-1}	Šarac et al. 2014
Satureja hortensis *Origanum heracleoticum* *Thymus vulgaris* *Rosa* × *damascena*	*Fusarium subglutinans* (Wollenw. & Reinking) P.E. Nelson, Toussoun & Marasas., *F. solani*, *F. tricinctum* (Corda) Sacc., *F. sporotrichioides* Sherb., *F. verticillioides* (Sacc.) Nirenberg., *F. oxysporum*, *F. semitectum* Berk. & Ravenel., *F. equiseti* (Corda) Sacc. *Aspergillus flavus*, *A. niger* *Gliocladium roseum* Bainier. *Curvularia lunata*	*In vitro*	0.07 a 0.9 mg mL^{-1}	Stević et al. 2014

Plant species	Phytopathogenic fungi	Evaluation	EO dose	Reference
Satureja hortensis *Origanum heracleoticum* *Thymus vulgaris* *Rosa* × *damascena*	*Verticillium dahliae* Kleb. *Trichoderma viride* Pers., *T. roseum* Pers. *Myrothecium verrucaria* (Alb. & Schwein.) Ditmar.	*In vitro*	0.07 a 0.9 mg mL^{-1}	Stević et al. 2014
Carum carvi *Ocimum citriodorum* *Origanum vulgare* *Pimenta racemosa* *Thymus satureoides* *Thymus vulgaris*	*Stachybotrys chartarum* (Ehrenb.) S. Hughes. *Cladosporium cladosporioides* *Aspergillus niger*	*In vitro*	1.0 µL mL^{-1}	Zabka et al. 2014
Origanum vulgare *Rosmarinus officinalis*	*Aspergillus niger*, *A. flavus*	*In vitro* *In vivo* (grapes)	0.25 µL mL^{-1} 1.0 µL mL^{-1}	de Sousa et al. 2013
Ruta angustifolia *Ruta chalepensis* var. *bracteosa* *Ruta graveolens* *Ruta tuberculate* Forssk.	*Aspergillus fumigatus*, *A. flavus* *Cladosporium herbarum* (Pers.) Link. *Fusarium oxysporum*	*In vitro*	10 µL disk	Haddouchi et al. 2013
Cinnamomum zeylanicum *Thymus vulgaris* *Ocimum basilicum* *Cuminum cyminum* *Pelargonium graveolens* *Cymbopogon citratus* *Litsea cubeba* (Lour.) *Pers.* *Mentha arvensis*	*Colletotrichum destructivum* O'Gara. *Phytophthora parasitica* var. *nicotianae* (Breda de Haan) Tucker.	*In vitro*	240 µg mL^{-1}	Lu et al. 2013
Eucalyptus globulus	*Mucor hiemalis* Wehmer. *Penicillium glabrum* (Wehmer) Westling. *Fusarium roseum* Link.	*In vitro*	1.5 a 5.0 µL mL^{-1}	Martins et al. 2013
Melaleuca alternifolia	*Botrytis cinerea*	*In vitro*	0.4 a 1.0 mL l^{-1}	Shao et al. 2013
Pulicaria mauritanica	*Penicillium expansum*	*In vitro*	2.0 µL mL^{-1}	Znini et al. 2013
Armoracia rusticana *Allium sativum* *Cinnamomum aromaticum*	*Aspergillus niger* *Penicillium digitatum*	*In vitro*	31.2 µL L^{-1} 62.5 µL L^{-1}	Kloucek et al. 2012
Citri-V	*Penicillium chrysogenum* *Aspergillus niger*	*In vitro* *In vivo* (Tomato)	Air - 15 mg L^{-1}	Phillips et al. 2012
Mazus goodenifolius (Hornem.) Pennell.	*Rhizopus solani*	*In vitro*	20 mg mL^{-1}	Riaz et al. 2012
Cicuta virosa var. *latisecta*	*Aspergillus flavus*, *A. oryzae* (Ahlb.) Cohn., *A. niger*	*In vitro* *In vivo* (Cherry tomato)	5 µL mL^{-1} 200 µL mL^{-1}	Tian et al. 2011a

Plant species	Phytopathogenic fungi	Evaluation	EO dose	Reference
Anethum graveolens	*Aspergillus flavus*, *A. oryzae*, *A. niger*	*In vitro* *In vivo* (Cherry tomato)	2.0 μL mL^{-1} 120 μL mL^{-1}	Tian et al. 2011b
Thymus vulgaris *Citrus aurantifolia*	*Colletotrichum gloeosporioides*	*In vitro* *In vivo* (papaya)	0.085 % (v/w) 0.15% (v/w)	Bosquez-Molina et al. 2010
Origanum vulgare *Verbena officinalis* *Thymus vulgaris*	*Botrytis cinerea* *Penicillium italicum* *Phytophthora citrophthora* R.&E. Sm. *Rhizopus stolonifer*	*In vitro* *In vivo* (orange)	250 ppm 2000 ppm	Camele et al. 2010
Citrus maxima *Citrus sinensis*	*Aspergillus flavus*	*In vitro*	750 ppm	Singh et al. 2010

Does not include the species *Alternaria alternata*. Citri-V = 50:50 mix of orange and bergamot essential oil.

Mechanisms of action of EOs on phytopathogenic fungi

The action mechanism of the EOs on fungi is not entirely known. However, Rivera et al. (2015) proposed that the antimicrobial action is attributed to their ability to penetrate through the cell membranes and inhibit the functional properties of the cell by causing severe damage to organelles. There are different microscopy techniques used to observe these physical alterations. Overall, the Optical Microscopy and Scanning Electron Microscopy (SEM) are used to recognize the morphological changes in fungi. In contrast, the Transmission Electron Microscopy (TEM) is used to look into cellular alterations.

It is generally reported in the literature that, in control treatments, the fungi presented mycelium with regular morphology, healthy development, abundant conidia, and round hyphae with smooth external surfaces, constant diameter, and integral membranes. On the contrary, in EOs-treated fungi, it was possible to observe different morphological alterations and structural damage, which increased depending on the concentration.

For example, the application of the cinnamon EO (*C. zeylanicum*) in *Alternaria alternata* (Fr.) Keissl., produce alterations in its hyphae collapse, crushing, emptying, and lysis of the cell wall, and with aggregates of wrinkled hyphae (Lu et al. 2013). In other studies, thyme EO (*T. vulgaris*) affected the conidia germination (and in some cases, the total absence of these) together with a delay in the development of the germinative tube, rupture of the cell wall and the conidia plasma membrane, with disorganization of the cytoplasm and destruction of organelles (Perina et al. 2014), while citronella EO (*Cymbopogon nardus* (L.) Rendle.) affected the mycelial morphology with empty, folded, and flattened hyphae, with a rough and deformed surface, with the absence of conidia (Chen et al. 2014).

In the same fungus, with laurel EO (*L. nobilis*), the mycelium was degraded with folds and wrinkles on the cell walls surface and few visible spores (Xu et al. 2014). Za'atar EO (*Z. multiflora*) is reported to cause the granulation of cytoplasm, inhibition of mycelial growth, decrease and loss in the conidia formation, inhibition of conidial germination and shortening of the germinative tubes, as well as, a reduction in the diameter of hyphae (with sub-apical germination and with anomalous bulbous structures at its tips), collapse and wrinkling of hyphae and production of chlamydoconidia in old hyphae (Mahmoudi et al. 2012).

In other phytopathogenic fungi, the damages observed were similar. For example, *A. flavus* incubated in peppermint EO (*M. spicata*), presented hyphae distorted with collapsed conidia and depressions in the surface. Also, through TEM observations, plasma membrane rupture, leakage of cellular material, and decrease of the cellular matrix (Kedia et al. 2015) were documented, while *A. niger* treated with dill EO (*A. graveolens*) showed deformation of the conidia, with

severe damage, rupture and loss of integrity in these structures, as well as, craters in the vesicles, aggregates of wrinkled hyphae, decrease in diameter, collapse and flattening (Tian et al. 2011b).

In *B. cinerea*, tea tree EO (*M. alternifolia*) inhibited fungal growth and spore germination, and empty, collapsed, flat hyphae also occurred. Observations by TEM showed that the cell wall was destroyed. Therefore, the cell membrane permeability increased, in addition to cytoplasm coagulation by a higher density of electrons, increased mitochondrial volume, and loss of organelles (Shao et al. 2013).

In *Colletotrichum destructivum* O'Gara., thyme EO (*T. vulgaris*) caused considerable mycelium damage as aggregates of wrinkled, collapsed, crushed, and empty hyphae, and cinnamon EO (*C. zeylanicum*) on *Phytophthora parasitica* var. *nicotianae* (Breda de Haan) Tucker. caused alterations similar to those mentioned for *C. destructivum* (Lu et al. 2013).

Use of EOs as components of coatings and bioactive films for controlling phytopathogenic fungi

On the issue of antimicrobial substances, EOs are useful for controlling phytopathogenic fungi. However, their direct application in food brings about some problems: rapid volatility, aroma transfer, and toxicity. For this reason, its use has been studied in films and coatings, which allows them to minimize application doses; also, their gradual migration from the matrix allows their release to be scheduled (Ouattara et al. 2000; Sánchez-González et al. 2011).

On the use of biodegradable polymers for the development of coatings and edible films to which EOs were added and which were later evaluated in the control of phytopathogenic fungi (Table 3), it was found that 47.3% of the works focused on the development of coatings (Guerra et al. 2015; Vu et al. 2011), and an equal percentage on film development (47.3%) (Avila-Sosa et al. 2010; Hemalatha et al. 2017; Pola et al. 2016).

The EOs most used in the formulations were those from oregano (*O. vulgare*) (Barreto et al. 2016; Raphaël and Meimandipour 2017), and thyme (*T. vulgaris*) (Bill et al. 2014; Yahyaoui et al. 2016), followed by lemongrass (*C. citratus*) (Avila-Sosa et al. 2012; Ben-Fadhel et al. 2017), and cinnamon (*C. zeylanicum*) (Mateo et al. 2017; Noshirvani et al. 2017). As for phytopathogenic fungi, the most evaluated were *A. niger* (12 cases) (Barreto et al. 2016, Ben-Fadhel et al. 2017, Hemalatha et al. 2017), followed by *R. tolonifera* (Pola et al. 2016; Ramos-García et al. 2012), and *Penicillium expansum* Link. (Gniewosz et al. 2013; Guerra et al. 2016).

The studied model varied between coatings and films. On coatings, evaluations were conducted on cherry tomato (*Solanum lycopersicum* var. *cerasiforme* (Dunal) D.M. Spooner, G.J. Anderson & R.K. Jansen.) (Barreto et al. 2016), grape (*V. labrusca*) (dos Santos et al. 2012), tomato (*S. lycopersicum* L.) (Ramos-García et al. 2012), broccoli (*Brassica oleracea* var. *Itálica* Plenck.) (Ben-Fadhel et al. 2017), avocado (*Persea americana* Mill.) (Bill et al. 2014), and strawberry (*Fragaria × ananassa* (Duchesne ex Weston) Duchesne ex Rozier.) (Vu et al. 2011). On the other hand, 88.8% of the work with films was carried out in vitro and a few in carrots (*Daucus carota* L.) (Gniewosz et al. 2013).

Table 3. Biodegradable polymers added with EOs for the development of coatings and films, and their evaluation on phytopathogenic fungi.

Polymeric matrix	EOs	Type	Phytopathogenic fungi	Assay	Reference
Alginate (1.3 g) Glycerol (1.6%) Sodium diacetate (0.5%) Natamycin (0.008%) Sunflower oil (0.1%) Tween 80: Span 20 (0.13%)	*Cymbopogon citratus* (0.03%)	C	*Aspergillus niger*	Broccoli	Ben-Fadhel et al. 2017
Chitosan (16 mg mL^{-1})	*Origanum vulgare* (1.25 µg mL^{-1})	C	*Rhizopus stolonifer* *Aspergillus niger*	Cherry tomato	Barreto et al. 2016

Polymeric matrix	EOs	Type	Phytopathogenic fungi	Assay	Reference
Chitosan (4 y 8 mg mL^{-1})	*Mentha piperita* L., *Mentha* × *villosa* Huds. (1.25, 2.5, 5.0 μL mL^{-1})	C	*Aspergillus niger* *Botrytis cinerea* *Penicillium expansum* *Rhizopus stolonifer*	Grape	Guerra et al. 2016
Chitosan (4 mg mL^{-1})	*Mentha piperita*, *Mentha* × *villosa* (1.25, 2.5 μL mL^{-1})	C	*Aspergillus niger* *Botrytis cinerea* *Penicillium expansum* *Rhizopus stolonifer*	Cherry tomato	Guerra et al. 2015
Chitosan (1.0%) Arabic gum (10%) *Aloe vera* (2.0%)	*Thymus vulgaris* (1:1 y 3:1)	C	*Colletotrichum gloeosporioides*	Avocado	Bill et al. 2014
Chitosan (20 mg mL^{-1})	*Origanum vulgare* (1.25, 2.5, 5.0 mL mL^{-1})	C	*Rhizopus stolonifer* *Aspergillus niger*	Grape	dos Santos et al. 2012
Chitosan (1.0%) Beeswax (0.1%) or oleic acid (1.0%) Glycerol (0.3%)	Lime Thyme (0.1%)	C	*Rhizopus stolonifer*	Tomato	Ramos-García et al. 2012
Modified chitosan (2.0%) Tween 80 (0.4%)	*Oreganum compactum* *Thymus vulgaris* *Mentha piperita* *Cymbopogon citratus* (DC.) Stapf. (0.02%)	C	*Botrytis cinerea* *Rhizopus stolonifer*	Strawberries	Vu et al. 2011
Chitosan (1.0 g)	*Ocimum basilicum* (0.1, 0.3, 0.5%)	F	*Aspergillus niger*, *A. flavus* *Fusarium* sp. *Penicillium* sp.	*In vitro*	Hemalatha et al. 2017
Chitosan (1 g) Tween 20 (0.5%)	Oregano + Thyme (1.0%)	F	*Aspergillus niger*	*In vitro*	Kana and Meimandi 2017
Ethylene vinyl alcohol copolymer (13 g)	*Origanum vulgare* *Cinnamomum zeylanicum* (10%)	F	*Aspergillus flavus*, *A. parasiticus*	*In vitro*	Mateo et al. 2017
Chitosan (0.4 g) Carboxymethylcellulose (0.8 g) Tween 80 (0.8 mL) Glycerol (0.2 mL)	Cinnamon (4.4, 8.8, 13.2%) Ginger (3.5, 7.0, 10.6%)	F	*Aspergillus niger*	*In vitro*	Noshirvani et al. 2017
Cellulose acetate (8.0 g) Acetone (80 mL) Montmorillonite (0.2 g)	*Origanum vulgare* (0, 20, 40, 60%)	F	*Geotrichum candidum* *Rhizopus stolonifer*	*In vitro*	Pola et al. 2016
Poly (lactic acid) (0.5 g)	Myrtle Rosemary Thyme (0.5, 1.5, 2.0, 5.0%)	F	*Aspergillus niger*	*In vitro*	Yahyaoui et al. 2016

Polymeric matrix	EOs	Type	Phytopathogenic fungi	Assay	Reference
Pullulan (7.5 g 100 mL^{-1}) Glycerol (1.5 g 100 mL^{-1})	*Carum carvi* (0.12, 1.25, 2.5, 5.0, 8.0, 10 g 100 mL^{-1})	F	*Aspergillus niger* *Penicillium expansum*	Carrot	Gniewosz et al. 2013
Amaranth flour (4.0%) Chitosan (1.5%) Corn starch (1.0 g) Glycerol (1.3%) Tween 20 (0.5%)	*Lippia berlandieri* Schauer. *Cinnamomum verum* J.Presl. *Cymbopogon citratus* (0, 0.25, 0.50, 0.75, 1.0, 2.0, 4.0%)	F	*Aspergillus niger* *Penicillium digitatum*	*In vitro*	Avila-Sosa et al. 2012
Amaranth flour (4.0%) Chitosan (1.5%) Corn starch (1.0 g) Glycerol (1.3%) Tween 20 (0.5%)	*Lippia berlandieri* (0, 0.25, 0.50, 0.75, 1.0, 2.0, 4.0%)	F	*Aspergillus niger* *Penicillium* spp.	*In vitro*	Avila-Sosa et al. 2010
Chitosan (0.5 g) Caffeic acid (221 mg)	*Cuminum cyminum* (100 a 500 ppm)	N	*Aspergillus flavus*	*In vitro*	Zhaveh et al. 2015

C = coating, F= film, N = nanogel.

Conclusions

EOs have great potential to be used in the control of phytopathogenic fungi. According to the cases reported, it was established that their effect not only occurs *in vitro* and through its direct application, but also when integrated into coatings and films. This offers a viable alternative for the development of novel technologies, such as the integration of EOs into bioactive packaging (nets, bags, etc.), which would allow their application in different stages of crop development, and perhaps by extending its antifungal effect during the shelf-life of horticultural commodities, the adverse effects of the use of chemical products on consumers and on the environment would be minimized.

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