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Essential Oil: Innovative Tool to Improve the Preservation of Fresh Produce – A Review

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ABSTRACT

The degree of fresh produce safety obtained with the currently applied preservation methods seems to be not sufficient. The interest in the possible use of natural compounds to prevent microbial growth has notably increased in response to the consumer pressure to reduce or eliminate chemically synthesized additives in foods. This review examines the potency of essential oils as natural antimicrobial agents from plants, outlining the ranges of microbial susceptibility and factors affecting antimicrobial action. Moreover, an overview on the application of essential oils and/or components during storage on fruit quality related attributes as well as the impacts of essential oil on fruit coating edible films are demonstrated. Undesirable organoleptic effects can be limited by careful selection of essential oils according to the type/sensitivity of fresh commodity.

Keywords: antimicrobial, decay, coating edible films, fruit quality, postharvest treatments
Abbreviations: **•OH**, hydroxyl radicals; **$^1O_2$**, singlet oxygen; **ABTS**, 2,2'-azinobis(3-ethylbenzothiazoline-6-sulfonic acid) diammonium salt; **BA_{50}**, bactericidal activity; **CFU**, colony forming unit; **DPPH**, 2,2-di-(4-tertoctylphenyl)-1-picrylhydrazyl; **EO**, essential oil; **GRAS**, Generally Regarded as Safe; **O_2•−**, superoxide radicals; **ORAC**, oxygen radical absorbance capacity; **TA**, titratable acidity; **TSS**, total soluble solids

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INTRODUCTION

Food safety is an increasingly important public health issue despite the modern improvements in slaughter hygiene and food production techniques. It has been estimated that as many as 30% of people in industrialised countries suffer from a food borne disease each year (WHO 2002). At the same time, Western society appears to be experiencing a trend of 'green' consumerism (De Silva 1996), desiring fewer synthetic food additives. Most perishable food products are stored at low temperature and sometimes they are packaged under modified atmosphere in order to extend their shelf-life. However, these steps do not eliminate undesirable microorganisms from these products. Alternative preservation techniques such as pulsed light, high pressure, pulsed electric and magnetic fields, irradiation and natural antimicrobial ingredients are being used or investigated for their application to food products. The postharvest use of chemicals as fungicides is restricted in most countries. Moreover, most of the synthetic preservatives produce several side-effects as carcinogenicity, teratogenicity and residual toxicity (Basilico and Basilico 1999). Besides, consumers demand agricultural commodities without pesticide residues. Thus, new preservation technologies are needed, which have to be considered as human-safe, environmentally friendly and reduce or eliminate food borne pathogens, possibly in combination with existing methods. One possible candidate is the use of essential oils (EOs) as antimicrobial agent.

EOs, also called volatile or ethereal oils; are aromatic oily liquids obtained from plant material (flowers, buds, seeds, leaves, twigs, bark, herbs, wood, fruits and roots). EOs are not as broad spectrum as synthetic pesticides, but their effectiveness can be improved by using them in conjunction with carefully designed packaging. The presence of free moisture in a package provides the ideal environment for the growth of many postharvest pathogens. Most of the research to date has been done testing the growth of microbes in the laboratory under ideal conditions. The difficulty may be to apply the oils effectively under commercial conditions. EOs are often fungistatic rather than fungicidal. This means that they stop the growth of the fungi while it is exposed to the oil, but once the oil is removed the fungi can continue to grow. Application of the oil as a vapour at a continuous, low concentration should prevent tainting of the product. Thin skinned products, not

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surprisingly are more prone to tainting than those with thicker skins. EOs which have been registered as food additives are much easier to register for postharvest use than new synthetic pesticides. Application of these oils via the vapour phase should also make their use more cost effective than dipping (Jobling 2000).

It has long been recognised that some EOs have antimicrobial properties (Boyle 1955). Besides antibacterial properties (Deans and Ritchie 1987; Mourey and Canillac 2002; Burt 2004), EOs or their components have been shown to exhibit antiviral (Bishop 1995), antimycotic (Jayashree and Subramanyam 1999; Mari *et al.* 2003), antitoxigenic (Ultee and Smid 2001; Juglal *et al.* 2002), antiparasitic (Pessoa *et al.* 2002), herbicidal (Setia *et al.* 2007) and insecticidal (Nikpay 2007) properties. These characteristics are possibly related to the function of these compounds in plants (Mahmoud and Croteau 2002).

The purpose of this paper is to provide an overview of the published data on the antimicrobial activity of those EOs and their components that could be considered suitable for application in or on fresh produce as a food preservative as well as the impacts on fruit quality related characteristics.

CURRENT USE OF ESSENTIAL OILS

The greatest use of EOs in the European Union is in food (as flavourings), perfumes (fragrances and aftershaves) and pharmaceuticals (for their functional properties). Individual components of EOs are also used as food flavourings, either extracted from plant material or synthetically manufactured (Oosterhaven *et al.* 1995). The antimicrobial properties of EOs and their components are exploited in such diverse commercial products such as in meat and meat products, in pork liver sausage, in fish, in dairy products such as yoghurt and cucumber salad, in milk, in rice, in cheese, on bread and bakery products, in/on fruit and vegetables, in sweets, ice cream, beverages, and chewing gum (as reviewed by Burt 2004; Rojas-Gra *et al.* 2006). EOs are designated as Generally Regarded as Safe (GRAS) and are regarded as alternatives to chemical preservatives, and their use in foods meets the safety demands of consumers for mildly processed natural products, as reviewed by Burt (2004). The most commonly used method for producing EOs on a commercial basis is steam distillation.

ANTIMICROBIAL PROPERTIES OF PLANT ESSENTIAL OILS

For combating infectious or parasitic agents, plants synthesize secondary metabolites which may be present constitutively (Rauha *et al.* 2003) or generated from inactive precursors in response to stress (Sofos *et al.* 1998). Preformed substances (pro- or inhibitins) in plant tissue include phenolic compounds, flavonols, flavonoids, glycosides, alkaloids, and even polyacetylenes. Post-inhibitins are stored as inactive precursors which are activated by hydrolases or oxidases, usually in the plant tissue (Delaquis and Mazza 1995).

The composition, structure as well as functional groups of the oils play an important role in determining their antimicrobial activity. Usually compounds with phenolic groups are most effective (Dorman and Deans 2000). Among these, the oils of clove (*Sygzium aromaticum* L.), oregano (*Origanum vulgare* L.), rosemary (*Rosmarinus officinalis* L.), cinnamon (*Cinnamomum zeylanicum* L.), thyme (*Thymus capitatus* L.) and sage (*Salvia officinalis* L.) have been found to be most consistently effective against microorganisms. Plant EOs have been widely tested against fungi as well as both Gram-positive and -negative bacteria. The antimicrobial activity of EOs or components is well documented (as reviewed by Deans and Ritchie 1987; Arras *et al.* 1994; Sivropoulou *et al.* 1996; Reddy *et al.* 1998; Plotto *et al.* 2003; Burt 2004; Lee *et al.* 2007; Tzortzakis 2007a; Tzanakaki and Tzortzakis 2008). It is apparent that the generally greater resistance of Gram-negative bacteria to EOs (Walsh *et al.* 2003) is likely to be due in part to the greater complexity of the double membrane-containing cell envelope of these organisms in contrast with the single membrane glycoprotein/techoic acid, or membrane-glycoprotein/β-glucan-based structures of Gram-positive bacteria and yeast, respectively. While this is true of many EOs, there are some which are effective against both groups (oregano, clove, cinnamon and citral; Sivropoulou *et al.* 1996). There are also some nonphenolic constituents of oils which are quite effective against Gram-negative bacteria (garlic oil (*Allium sativum* L.); Yin and Cheng 2003). Considering the large number of different groups of chemical compounds present in EOs, it is most likely that their antimicrobial activity is not attributable to one specific mechanism but that there are several targets in the cell (Carson *et al.* 2002). A number of potential synergists have been suggested for use with EOs: low pH, low water activity, chelators, low oxygen tension, mild heat and raised pressure, although not all of these have been researched in foodstuffs (Gould 1996).

Due to their ability to grow in almost all food products, yeasts and moulds can generate off-flavours, produce toxin, and cause discolouration and proteolysis through the action of various enzymes like lipases and proteases. The most important feature of moulds from a food safety perspective is their ability to produce mycotoxins, such as aflatoxins, which are toxigenic secondary metabolites. *Aspergillus ochraceus* produces ochratoxin A which is responsible for nephropathies in pigs and humans.

IMPACTS OF ESSENTIAL OIL ON FRESH PRODUCE PRESERVATION

Postharvest decay is one of the major obstacles in the postharvest fruit chain, reducing the commercial value of fresh produce. Due to the economical impacts of spoiled foods and the consumer's concerns over the safety of foods containing synthetic chemicals, a lot of attention has been paid to naturally derived compounds or natural products such as EOs from aromatic plants with antimicrobial activities for controlling pathogens and/or toxin producing microorganisms in foods. An overview of EOs studies presented in **Table 1**, and analyzed as follows.

Strawberries (*Fragaria ananassa* Duch.) treated with EO (0.1 ml/l) of tea-tree oil (*Melaleuca alternifolia* L.) reduced 34% the severity of decay during storage at 10°C as compared to the control (Chanjirakul *et al.* 2007). Moreover, thyme oil volatiles (0.05-0.2 ml/l) examined as an antifungal preservative for strawberry fruits and suppressed *Botrytis cinerea* (up to 76%) and *Rhizopus stolonifer* (up to 75%) development, resulting in decreased decay with increases in oil volatile concentration (Reddy *et al.* 1998). Additionally, fruit decay decreased in strawberry-treated with cinnamon (*C. zeylanicum* L.) or eucalyptus (*Eucalyptus citriodora* L.) oil (0.05-0.5 ml/l) vapours and transferred/stored to chilled air (Tzortzakis 2007b). EOs of clove, cinnamon, oregano, cinnamaldehyde-enriched cinnamon EO when used (4% v/v) in paraffin-based "active coatings" for paper packaging materials protected strawberry against fungi and there were no apparent visible or organoleptic changes in the fruit (Rodrıguez *et al.* 2007).

Several studies examined the impact of EOs and/or compounds on severity of berries. Thus, blackberries (*Rubus fruticosus* L.) and raspberries (*Rubus idaeus* L.) treated with EO (0.1 ml/l) of tea-tree oil reduced 22 and 48% respectively, the severity of decay during storage at 10°C as compared to the control (Wang 2003; Chanjirakul *et al.* 2007). Moreover blueberries (*Vaccinium corymbosum* L.) exposed to several EOs (200 mg/l, including carvacrol, anethole, cinnamaldehyde, cinnamic acid, perillaldehyde, linalool, and p-cymene) inhibited fruit decay (Wang *et al.* 2008).

Azizi *et al.* (2006) reported that radial growth and spore germination of important citrus postharvest fungi (*Penicillium italicum*, *Penicillium digitatum* and *Alternaria citri*) were decreased (up to 59%) and/or completely inhibited when fruits exposed to different concentrations (250, 500 and 1000 mg/l) of EOs of thyme, mint, summer savory

Table 1 Effect of essential oil or components on postharvest pathogens of fruit and vegetables.

Essential oil or Component	Commodity	Pathogen(s)	Essential oil conc. (mg/l or ml/l, mM, %w/v, %v/v or purity)	Effects		Reference
				Antimicrobial	Produce Quality	
Eugenol; thymol; menthol; eucalyptol	Cherry	Moulds, yeasts, Total aerobic mesophilic	(99.5% purity)	+	±	Serrano *et al*. 2005
Thymol; carvacrol		*Botrytis cinerea*, *Monilinia fructicola*	1000 mg/l (dipping)	+	-	Chu *et al*. 1999; Tsao and Zhou 2000
Eucalyptus oil;	Apple	*Botrytis cinerea*	0.004-0.008 ml/l	+	Na	Lee *et al*. 2007
Cumin oil			0.005-0.010 ml/l	+	Na	
Clove oil		*Penicillium expansum; Botrytis cinerea; Colletotrichum gloeosporioides; Macrophoma kawatsuka; Monilia fructigena; Trichothecium roseum*	1.5-3.5 mg/l	+	+	Li *et al*. 2006
Oregano oil; lemongrass oil; cinnamon oil	Apple puree film coating	*Escherichia coli*; *Listeria innocua;* Psychrophilic aerobes; yeasts; molds	0.05, 0.075, 0.1, 0.3-0.5-0.6-1.0-1.5% (w/w)	+	±	Rojas-Grau *et al*. 2006, 2007
Cinnamon oil; clove bud oil; lemongrass oil; bitter orange oil; mandarin oil; sweet orange oil; lemon oil; tangerine oil; lime oil; grapefruit oil; palmarosa oil		*Escherichia coli*; *Salmonella enterica*	1% (v/v)	+	Na	Friedman *et al*. 2004
Soybean oil; corn oil; peanut oil; olive oil; linseed oil; cottonseed oil		-	3%, 6%, 9% (w/v)	Na	+	Ju *et al*. 2000a
Vanillin		*Escherichia coli*; *Salmonella enterica*	12 mM	+	Na	Moon *et al*. 2006; Rupasinghe *et al*. 2006; Rojas-Grau *et al*. 2006, 2007
Thymol	Apricots	*Monilinia fructicola*	1-2-4-8 mg/l	+	+, -	Liu *et al*. 2002
Thymol	Plums	*Monilinia fructicola*	1-2-4-8 mg/l	+	+	Liu *et al*. 2002
Soybean oil; corn oil; peanut oil; linseed oil; cottonseed oils	Pears	-	3%, 6%, 9% (w/v)	Na	+	Ju *et al*. 2000b, 2000c
Cinnamon oil	Pears film coating	-	0.06 ml/l	Na	+	Gou *et al*. 2008
Origanum oil; basil oil; thymus oil	Kiwifruit	*Botrytis cinerea*	0.50 ml/l	+	-	Thanassopoulos and Yanna 1997
Carvacrol; cinnamic acid		Total viable counts	5-15 mM	+	-	Roller and Seedhar 2002
Limonene	Kumquat	*Penicillium digitatum*	5 ml/l	+	Na	Ben-Yehoshuan *et al*. 2008
Vanillin	Pineapple film coating	*Escherichia coli; Saccharomyces cerevisiae*	9000 mg/l	+	+	Sangsuwana *et al*. 2008
Ceylon citronella oil;	Banana	*Fusarium sp., Lasiodiplodia*	0.4%	+	+	Anthony *et al*. 2003
Lemograss oil;		*theobromae* & *Colletorhum*	0.16%	+	–	Anthony *et al*. 2003
Basil oil		*musae* (crown rot disease complex); *Colletorhum musae*	0.16%	++	0	Anthony *et al*. 2003
Cinnamon oil		*Fusarium sp., Lasiodiplodia theobromae* & *Colletorhum musae* (crown rot disease complex) *Colletorhum musae*	0.03-0.11%	+	Na	Ranasinghe *et al*. 2002
			0.16-0.22%	+	0	Ranasinghe *et al*. 2005
Clove oil		*Fusarium sp., Lasiodiplodia theobromae* & *Colletorhum musae* (crown rot disease complex) *Colletorhum musae*	0.03-0.11%	+	Na	Ranasinghe *et al*. 2002
			0.02%	0	0	Ranasinghe *et al*. 2005
Lemongrass oil	Mango	*Colletotrichum gloeosporioides*	40 ml/l (dipping)	+	Na	Duamkhanmanee 2008
Limonene hydroperoxides	Lemon	*Penicillium digitatum*	-	+	Na	Ben-Yehoshuan *et al*. 2008
Mint oil;	Orange	*Penicillium italicum*	0.1 ml/l	+	Na	Tripathi *et al*. 2004
Basil oil;			0.2 ml/l			
Ginger oil			0.5 ml/l			
Mint oil;	Lime	*Penicillium italicum*	0.1 ml/l	+	Na	Tripathi *et al*. 2004
Basil oil;			0.2 ml/l			
Ginger oil			0.5 ml/l			
Thyme oil; mint oil; savory oil; cumin oil; Ajowan caraway oil	Orange	*Penicillium italicum*; *Penicillium digitatum*; *Alternaria citri*	75-150-250 mg/l	+	Na	Azizi *et al*. 2006
Dill oil; coriander oil; cumin oil; rosemary oil; thyme oil		*Penicillium digitatum*	0.3-0.6-0.9 ml/l	+	Na	Yigin et al. 2000

Table 1 (Cont.)

Essential oil or Component	Commodity	Pathogen(s)	Essential oil conc. (mg/l or ml/l, mM, %w/v, %v/v or purity)	Effects		Reference
				Antimicrobial	Produce Quality	
Thyme oil;	Mandarin	*Penicillium digitatum*	0.02 ml/l	+	+	Arras *et al*. 1994
Goatweed oil		*Penicillium italicum*	0.1-0.2-0.3%	+	0	Dixit *et al*. 1995
Tea-tree oil	Blackberries	Fruit decay	0.1 ml/l	+	+	Chanjirakul *et al*. 2007
Carvacrol; anethole; cinnamaldehyde; cinnamic acid; perillaldehyde; linalool; *p*-cymene	Blueberries	Fruit decay	200 mg/l	+	+	Wang *et al*. 2008
Ttea tree oil	Raspberries	-	0.1 ml/l	+	+	Wang 2003; Chanjirakul *et al*. 2006
Thyme oil	Strawberry	*Botrytis cinerea, Rhizopus stolonifer*	0.05- 0.1-0.2 ml/l	+	Na	Reddy *et al*. 1998
Tea-tree oil		Fruit decay	0.1 ml/l	+	+	Chanjirakul *et al*. 2007
Eucalyptus oil; cinnamon oil		Fruit decay	0.05-0.5 ml/l	+	+	Tzortzakis 2007b
Cinnamon oil; thyme oil; oregano oil		*Eurotium repens*, *Penicillium nalgiovense*, *Penicillium roqueforti*, *Aspergillus flavus*	4%	++	+	Rodrıguez *et al*. 2007
Thymol; menthol; eugenol		Fruit decay	200 mg/l	+	+	Wang *et al*. 2007
Vanillin		Native and inoculated flora	3000 mg/l	+	Na	Cerrutti *et al*. 1997
eugenol, geraniol, citral			0.5% (v/v)	+	Na	Raybaudi-Massilia *et al*. 2008
Carvacrol; cinnamic acid	Melon	Total viable counts	5-15 mM	+	-	Roller and Seedhar 2002
Cinnamon leaf oil; palmarosa oil; lemongrass oil		*Salmonella enteritidis*; Native flora,	0.3-0.7%	+	+ -	Raybaudi-Massilia *et al*. 2008
Lemongrass oil	Melon seeds	*Aspergillus flavus*; *Aspergillus niger*; *Aspergillus tamari*; *Penicillium citrinum*	0.1-0.25-0.5-1.0 ml/100 g seeds	+	+	Bankole *et al*. 2005
Eucalyptus oil; cinnamon oil	Tomato	Fruit decay	0.05-0.5 ml/l	+	+	Tzortzakis 2007b
White thyme oil; oregano oil; lemongrass oil		*Botrytis cinerea; Rhizopus stolonifer*; *Geotrichum candidum; Alternaria arborescens*	50 mg/l (Fumigant) 100-500-1000-5000-10000 mg/l (Dipping)	- ±	- -	Plotto *et al*. 2003
Cinnamon oil		*Colletotrichum coccodes*; *Botrytis cinerea*	0.05-0.5 ml/l	±	Na	Tzortzakis 2009
Origanum oil		*Colletotrichum coccodes*; *Alternaria alternata*	0.4 ml/ l	+	+	Tzortzakis, unpublished data
Origanum oil; sage oil		*Botrytis cinerea; Colletotrichum coccodes*	0.01-0.05-0.10-0.50 ml/l	+	+	Tzanakaki and Tzortzakis 2008
Cassia oil (alone or with $MgSO_4$)		*Alternaria alternata*	0.2-0.3-0.4-0.5-1.0 ml/l	+	0	Feng and Zheng 2007; Feng *et al*. 2008
Thyme oil; summer savory oil; clove oil	Tomato paste	*Aspergillus flavus*	0.05-0.20-0.35-0.50 ml/l	+	-	Omidbeygi *et al*. 2007
Cinnamon oil;	Pepper	*Colletotrichum coccodes*;	0.05-0.5 ml/l	±	Na	Tzortzakis 2009
Origanum oil; sage oil		*Botrytis cinerea*	0.01-0.05-0.10-0.50 ml/l	+	+	Tzanakaki and Tzortzakis 2008
Lemograss oil; thyme oil	Onion	*Aspergillus niger*	0.10-0.15-0.20-0.40 ml/l	+	Na	Abd-Alla *et al*. 2006
Thyme oil; lemon balm oil	Lettuce	Total Viable Count; Lactic	0.25-0.5-1.0 ml/l	±	-	Gutierrez *et al*. 2008b
Oregano oil		Acid Bacteria; Enterobacteria;	0.25 ml/l			Gutierrez *et al*. 2008a
Oregano oil + thyme oil		*Pseudomonas*	0.15 ml/l+0.25 ml/l			
Thyme oil		*Escherichia coli*	0.1-10 ml/l	+	Na	Singh *et al*. 2002
Mint oil (Fungastop™)		Mesophilic aerobic microorganisms; mould; yeast	0.2% (w/v)	+	+	Martınez-Romero *et al*. 2008
Oregano oil;	Carrots	Total Viable Count; Lactic	0.25 ml/l	±	0	Gutierrez *et al*. 2008b
Oregano oil + thyme oil		Acid Bacteria; Enterobacteria; *Pseudomonas*	0.15 ml/l+0.25 ml/l			
Thyme oil		*Escherichia coli*	0.1-10 ml/l	+, ++	Na	Singh *et al*. 2002
Holy basil oil;	Table grapes	*Botrytis cinerea*	0.2 ml/l	+	+	Tripathi *et al*. 2008
Peach oil;			0.1 ml/l			
Ginger oil			0.1 ml/l			
Tea Tree oil		*Botrytis cinerea*	0.005-0.05-0.1-0.5 ml/l	+	-	Jobling 2000
Carvacrol		*Botrytis cinerea*	0.05-0.2- 0.5 -1.0 ml/l	+	+	Martínez-Romero *et al*. 2007
Thymol; menthol		Moulds; yeasts; Total aerobic mesophilic	0.5 ml/l	+	+	Martinez-Romero *et al*. 2005
Eugenol; thymol		Moulds; yeasts; Total aerobic mesophilic	(99.5% purity)	+	+	Valero *et al*. 2006

Table Key: Pathogen(*s*): — (not recorded)

Effects: + (controlled microbial growth/produce quality enhanced); ++ (complete elimination of surface microflora); - (no effect on or stimulation in microbial growth/adverse effect on produce quality); ± (variable dependent on storage conditions); Na (not assessed); 0 (no effect on microbial growth or produce quality)

(*Satureja hortensis* L.), cumin (*Cuminum cyminum* L.) and ajowan caraway (*Trachyspermum copticum* L.). Therefore, the inhibitory potency of EOs on the postharvest disease of orange (*Citrus sinensis* L.) fruits was as *Th. vulgaris*> *T. copticum*> *S. hortensis*> *C. cyminum*> *M. piperita* and the extent of inhibition of fungal growth depended on the concentration used. Likewise, Yigin *et al.* (2000) reported the antifungal activity of several EOs (dill (*Anethum graveolens* L.), coriander (*Coriandrum sativum* L.), cumin (*C. cyminum* L.), rosemary (*R. officinalis* L.), thyme (*Thymbra spicata* L.)) at 0.3-0.9 ml/l against green mold (*P. digitatum*), on oranges. Moreover, oils of mint (0.1 ml/l), ginger (*Zingiber officinale* L.) (0.2 ml/l) and ocimum (*Ocimum canum* L.) (0.5 ml/l) controlled blue mould rot (caused by *P. italicum*) of oranges and lime fruits during storage. The mint oil-treated oranges and lime fruits showed enhancement of storage life of 6 and 8 days, respectively. The storage life of ocimum oil-treated oranges and lime fruits was found to be enhanced by 6 days while in the case of ginger oil, it was 4 and 8 days enhancement of shelf life of oranges and lime fruits, respectively (Tripathi *et al.* 2004).

Mandarin (*Citrus reticulata* L.) fruits fumigated with thyme EO (0.02 ml/l) reduced up to 30% green mold comparing to the control (Arras *et al.* 1994). The goatweed (*Ageratum conyzoides* L.) oil (0.1-0.3% v/v) when employed by dipping and fumigation successfully controlled blue mould rot (*P. italicum*) of mandarins and imparted no adverse effect on the quality of treated fruits (Dixit *et al.* 1995).

Young mature-green lemons (*Citrus lemon* L.), produced greater limonene hydroperoxides and demonstrated significantly lower decay incidence than older yellow fruit when their oil glands were punctured in the presence of postharvest wound pathogen *P. digitatum* Sacc. Furthermore, wounding of the oil glands or injection of limonene hydroperoxides into the lemon peel elicited the production of the citrus fruit phytoalexins, scoparone and scopoletin, to levels known to be effective in reducing decay caused by *P. digitatum* (Ben-Yehoshuan *et al.* 2008).

In *in vivo* experiments, wound-inoculated apricots (*Prunus armeniaca* L.) and plums (*Prunus salicina* L.) were reduced (up to 95%) the incidence of brown rot (*Monilinia fructicola*) following fumigation with thymol (4-8 mg/l) (Liu *et al.* 2002). Fumigation of apricots with 2 mg/l of thymol vapor reduced the germination of *M. fructicola* conidia to 2% compared with 98% on untreated fruit. Microscopic observations showed that the fumigated spores fumigated with thymol were shrunken and had collapsed protoplasts (Liu *et al.* 2002).

EOs (1.5-3.5 mg/l) extracted from clove leaves (*Syringa portolaciniata* L.) reduced the rate of rotted fruits and inhibited to some extent pathogens (*Penicillium expansum*, *B. cinerea*, *Colletotrichum gloeosporioides*, *Macrophoma kawatsuka*, *M. fructigena* and *Trichothecium roseum*) grown in apples (*Malus domestica* L.) (Li *et al.* 2006). The EOs of eucalyptus (0.004-0.008 ml/l) and cumin (0.005-0.010 ml/l) displayed in vivo antifungal activity up to 59% and 37% against *B. cinerea* on artificially inoculated apples (Lee *et al.* 2007). Moreover, Friedman *et al.* (2004a) evaluated 17 plant EOs (apricot, bergamot (*Citrus aurantium* L.), cinnamon bark, cinnamon Cassia, cinnamon leaf, clove bud, grapefruit (*Citrus* × *paradisi*), lavender (*Lavandula angustifolia* L.), lemon, lemongrass (*Cymbopogon flexuosus* L.), lime, balm oil (Melissa; *Melissa officinalis* L.), orange bitter, orange Mandarin, orange sweet, oregano Spanish, tangerine (*Citrus reticulate* L.) and nine oil compounds (citral, eugenol, geraniol, linalool, linalyl acetate, terpinene, terpinen-4-ol, carvacrol, cinnamaldehyde) for antibacterial activity against the foodborne pathogens *Escherichia coli* O157:H7 and *S. enterica* in apple juices. The activity was greater for *S. enterica* than for *E. coli*, increased with incubation temperature and storage time, and was not affected by the acidity of the juices. Among the 10 most active compounds against *E. coli* (60 min BA_{50} range in clear juice, 0.018-0.093%) were carvacrol, oregano oil, geraniol, eugenol, cinnamon leaf oil, citral, clove bud oil, lemongrass oil, cinnamon bark oil, and lemon oil. The corresponding compounds against *S. enterica* (BA_{50} range, 0.0044-0.011%) were lemon balm oil, carvacrol, oregano oil, terpeineol, geraniol, lemon oil, citral, lemongrass oil, cinnamon leaf oil, and linalool. The bactericidal results are related to the composition of the oils (Friedman *et al.* 2004a).

Fumigation of sweet cherry (*Prunus avium* L.) with thymol was effective controlling gray mold and brown rot caused by previous inoculation with spores of *B. cinerea* and *M. fructicola* (Chu *et al.* 1999). Moreover, the microbial analysis showed that all EOs (eugenol, thymol, menthol and eucalyptol) reduced moulds and yeasts and total aerobic mesophilic colonies by 4- and 2-log CFU compared with control, respectively (Serrano *et al.* 2005). The brown rot incidences of *M. fructicola*-inoculated cherry dipped in 1000 mg/l thymol and carvacrol decreased up to 72% compared with the control. The effects of thymol and carvacrol were not significantly enhanced by the addition of $CaCl_2$ or CaB'y®, a foliar calcium fertilizer. Methyl jasmonate, an elicitor of plant defense mechanisms, reduced (69-73%) stem browning of cherry fruits only when used as a co-fumigant with thymol and carvacrol but not as an additive in dipping or fumigation experiments with thymol and carvacrol (Tsao and Zhou 2000).

Treatment with basil (*Ocimum basilicum* L.) oil (0.16% v/v), lemongrass (*C. flexuosus* L.) oil (0.16% v/v), cinnamon (*C. zeylanicum* L.) oil (0.03-0.22% v/v) and clove (*S. aromaticum* L.) oil (0.02-0.11% v/v) controlled crown rot disease complex (caused by *Fusarium* sp., *Lasiodiplodia theobromae* and *Colletorhum musae*) and anthracnose (*Colletorhum musae*) prolonging storage of bananas (*Musa acuminata* L.) up to 21 days at 13.5 ± 1°C (Ranasinghe *et al.* 2002; Anthony *et al.* 2003; Ranasinghe *et al.* 2005).

When lemongrass oil (40 ml/l) companied with hot water controlled better the anthracnose rot (*C. gloeosporioides*) compared with hot water treatment with carbendazim (at 100 mg/l) for mango (*Mangifera indica* L.) fruit (Duamkhanmanee 2008).

Freshly harvested kumquat (*Fortunella* sp.) fruits were dipped in an aqueous solution of sun-exposed limonene (5 ml/l) in 25% ethanol (plus 5 ml/l of Tween 20), and this treatment reduced decay (up to 87%) whereas fruit treated with 25% ethanol reduced decay only up to 34% (Ben-Yehoshuan *et al.* 2008).

Carvacrol and cinnamic acid, were found to delay the spoilage of fresh-cut kiwifruit (*Actinidia chinensis* L.) at chilling temperatures (Roller and Seedhar 2002).

The outcomes of several studies employing EOs as preservative mean on tomatoes (*Lycopersicon esculentum* L.) are differentiated. Plotto *et al.* (2003) reported that EOs (oregano, thyme, lemongrass, and coriander) vapors (50 mg/l) were not successful in stopping disease (*B. cinerea*, *Alternaria arborescens*, *R. stolonifer* and *Geotrichum candidum*) development in inoculated tomatoes. Additionally, some oil vapors appeared to induce phytotoxicity (introduced in different ratios or might be due to one or more compounds present in the oil) on treated fruit under long periods of exposure. In the same study, emulsions of oils of thyme and oregano at 5 ml/l and 10 ml/l as dip treatments reduced disease development in tomatoes inoculated with *B. cinerea* and *A. arborescens* (Plotto *et al.* 2003). However, origanum- (0.4 ml/l) and sage (0.01-0.50 ml/l)-treated tomatoes inhibited fungal development (*Colletotrichum coccodes*, *Alternaria alternata* and *B. cinerea*) (Tzanakaki and Tzortzakis 2008; Tzortzakis, unpublished data). Cassia (*Acacia farnesiana* L.) oil at 0.5 ml/l alone or in combination with $MgSO_4$ (0.25-3% w/v) reduced the percentage of decayed tomatoes (Feng and Zheng 2007; Feng *et al.* 2008). Fruit decay decreased in tomato-treated with cinnamon or eucalyptus oil (0.05-0.5 ml/l) vapours and transfer to chilled air (Tzortzakis 2007b). No differences observed on wound-inoculated tomato fruit after cinnamon oil (0.05-0.5 ml/l) exposure against *B. cinerea* and *C. coccodes* development. However, pre-exposing tomato fruit to 0.5 ml/l cinnamon

vapours for 3 days, and then inoculated with fungi, reduced *B. cinerea* and *C. coccodes* lesion development, extending 'memory' effects (Tzortzakis 2009). Antifungal activity (fungal growth inhibition) observed in EOs (0.05-0.5 ml/l) of thyme, summer savory and clove against *Aspergillus flavus* on tomato paste (Omidbeygi *et al.* 2007). Moreover, taste panel evaluations were carried out in a tomato ketchup base, and the percent of inhibition of each EO in tomato paste was lower than culture medium.

Wound-inoculated pepper (*Capsicum annuum* L.) fruit accelerated *B. cinerea* and *C. coccodes* development following 3 days vapour exposure (0.05-0.5 ml/l) to cinnamon (Tzortzakis 2009). Moreover, oregano and sage (0.01-0.5 ml/l) treated peppers reduced to some extent the fungal development of *C. coccodes* and *B. cinerea* (Tzanakaki and Tzortzakis 2008).

When Fungastop™ (a nature-based fungicide) sprayed on lettuce (*Lactuca sativa* L.) during field cultivation, had the same efficacy as chemical fungicides in terms of reducing microbial spoilage at harvest and delay in decay occurrence (between 1 and 2 weeks for both experiments) (Martinez-Romero *et al.* 2008). Initial decontamination effects of natural spoilage microflora (Total Viable Count, Lactic Acid Bacteria, *Enterobacteria*, *Pseudomonas*) as well as *E. coli* on ready-to-eat lettuce achieved using EOs of oregano and/or thyme (Singh et al., 2002; Gutierrez *et al.* 2009).

Tea tree oil at a concentration of 3.2% was as effective as three commercially recommended fungicides in decreasing *B. cinerea* colonization of white cabbage (*Brassica oleracea* L.) leaf discs (Bishop and Reagan 1998).

EOs of thyme and lemongrass (0.1-0.4 ml/l) inhibited black mould (*Aspergillus niger* L.) disease incidence in onion (*Allium cepa* L.) bulbs during storage periods of 7, 14, 21 and 45 days. Above concentration of 0.2 ml/l, thyme oil vapor gave a complete protective effect against disease incidence at all storage periods, whereas at 0.15 ml/l vaporized bulbs reduced disease incidence about 83% (Abd-Alla *et al.* 2006).

Initial decontamination effects of natural spoilage microflora (Total Viable Count, Lactic Acid Bacteria, *Enterobacteria*, *Pseudomonas*) as well as *E. coli* on ready-to-eat carrots (*Daucus carota* L.) obtained using EOs of oregano and/or thyme (Singh *et al.* 2002; Gutierrez *et al.* 2009).

Practical applicability of the EOs of ocimum (*Ocimum sanctum* L.) (0.2 ml/l), peach (*Prunus persica* L.) (0.1 ml/l) and ginger (*Z. officinale* L.) (0.1 ml/l) was observed in control of gray mould (caused by *B. cinerea*) of grapes during storage and the oils did not exhibit any phytotoxic effect on the fruit peel. The *O. sanctum*- and *P. persica*-oil-treated grapes showed enhancement of storage life up to 5 and 4 days respectively. The storage life of *Z. officinale*-oil-treated grapes was found to be enhanced up to 6 days (Tripathi *et al.* 2008). Active packaging was developed by adding eugenol or thymol (99.5% purity) to table grapes reduced microbial spoilage (moulds, yeasts and total aerobic mesophilic) on a dose response level (Valero *et al.* 2006). Thymol or menthol (0.5 ml) reduced yeasts, moulds and total aerobic mesophylic colonies by 3-log CFU on table grapes, and also improved the visual aspect of the rachis (Martinez-Romero *et al.* 2005). Moreover, carvacrol vapour (0.05-1.0 ml/l) inhibited the growth of *B. cinerea* in grapes dependent on carvacrol concentration (Martinez-Romero *et al.* 2007).

Melon (*Cucumis melo* L.) seeds inoculated with fungi (*A. flavus*, *A. niger*, *Aspergillus tamari* and *Penicillium citrinum*) and exposed to EOs of lemongrass at 0.1-1.0 ml/100 gr seeds inhibited fungal growth and significantly reduced deterioration and aflatoxin production in shelled melon seeds inoculated with toxigenic *A. flavus*. At higher dosages (0.5 and 1.0 ml/100 g seeds), the EOs completely prevented aflatoxin production. The oil content, free fatty acid and peroxide values in seeds protected with EO after 6 months did not significantly differ from the values in seeds before storage (Bankole *et al.* 2005). EOs (cinnamon, palmarosa (*Cymbopogon martini* L.) and lemongrass) and their main active compounds as natural antimicrobial substances incorporated into an alginate-based edible coating on fresh-cut melon revealed antimicrobial effects against *S. enteritidis* and prolonged shelf-life by more than 21 days (Raybaudi-Massilia *et al.* 2008). Carvacrol and cinnamic acid were found to delay the spoilage of fresh-cut honeydew melon at chilling temperatures without adversely affecting sensory quality (Roller and Seedhar 2002).

EFFECTS OF ESSENTIAL OIL ON FRESH PRODUCE QUALITY

Fruit quality encompasses many aspects, and includes not only flavour, colour, nutritional aspects and firmness, but also shelf life, processing attributes, resistance to pathogens and human health attributes (Brummell and Harpster 2001). EOs vapors may induce phytotoxicity on treated fruit under long periods of exposure and/or increased concentrations make them undesirable fresh commodities as well as increased risks of human health. Tomatoes treated with EOs for 24 hours observed phytotoxicity and it was apparent after 6 hours of fumigation if a fan was used to distribute the volatile oils (thyme, oregano and lemongrass) in the container. Phytotoxicity occurred whether tomatoes were fumigated with the EOs, or with the respective major components alone, indicating that at least the major compounds were contributing to the phytotoxicity (Plotto *et al.* 2003). Dispite the antifungal activity against brown rot (*M. fructicola*) of thymol on cherries, EOs vapors induced browning on the stems, affectd fruit quality (Tsao and Zhou 2000). Additionally, a residual taste from thymol on fumigated cherries made this mode of treatment not commercially applicable. Plant EOs may be effective to control postharvest diseases. However, much work remains to be done to develop a formulation that maintains the fungicidal activity of the material, and yet does not induce undesirable effects.

Impacts of essential oil on fruit quality characteristics

Strawberries treated with essential oil (0.1 ml/l) of tea-tree oil enhanced antioxidant capacity{antioxidant system such as oxygen radical absorbance capacity (ORAC), radical 2,2-di-(4-tertoctylphenyl)-1-picrylhydrazyl (DPPH), radical cation 2,2'-azinobis(3-ethylbenzothiazoline-6-sulfonic acid) diammonium salt (ABTS)} and free-radical scavenging capacity {superoxide radicals (O_2•−), hydroxyl radicals (•OH) and singlet oxygen ($^1O_2$)} during storage at 10°C as compared to the control (Chanjirakul *et al.* 2007). Indeed, strawberries treated with thymol, menthol, or eugenol maintained better fruit quality with higher levels of sugars, organic acids, phenolics, anthocyanins, flavonoids, and oxygen radical absorbance capacity than the untreated fruits. These data provide evidence that, in addition to possessing antimicrobial activity, the EOs also increase free radical scavenging capacity and antiproliferative activity in fruit and, in turn, enhance the resistance of fruit tissues to deterioration and spoilage (Wang *et al.* 2007). However, when fruit exposed to eucalyptus and cinnamon volatile oil compounds (0.05 or 0.5 ml/l) at 13°C during or following vapour exposure revealed not much effects on fruit quality related characteristics (Tzortzakis 2007b).

Blackberries treated with EOs (0.1 ml/l) of tea-tree oil enhanced antioxidant capacity {antioxidant system such as ORAC, DPPH, ABTS and free-radical scavenging (H_2O_2, •OH) during storage at 10°C as compared to the control (Chanjirakul *et al.* 2007).

The postharvest quality of raspberries was improved (increased levels of sugars, organic acids, oxygen radical absorbance capacity and darker colour) after treatment (0.1 ml/l) with tea tree oil and storage at 0, 10 or 20°C compared with untreated fruit (Wang 2003). Moreover, treated fruits increased antioxidant capacity or the antioxidant enzyme activities (Chanjirakul *et al.* 2006).

Several naturally occurring EOs (200 mg/l) including

carvacrol, anethole, cinnamaldehyde, cinnamic acid, perillaldehyde, linalool, and *p*-cymene increased antioxidant levels and activities in 'Duke' blueberries. Thus, total anthocyanins and total phenolics promoted following EOs treatment, and enhanced antioxidant activity in fruit tissues. Individual flavonoids were variably affected by the EOs. Additionally, treatment with carvacrol, anethole, or perillaldehyde increased the levels of fructose, glucose, and citric acid (Wang *et al.* 2008).

It has been reported that thyme EOs (0.02 ml/l) caused no injury in flavedo of ripe mandarin fruits (Arras *et al.* 1994).

Fumigation of apricots with thymol resulted in firmer fruit and higher surface browning, but total soluble solids (TSS) and titratable acidity (TA) were not affected. Fumigation of plum with thymol resulted in higher TSS, but firmness and TA were not affected. Indeed, thymol fumigation caused phytotoxicity on apricots but not on plums (Liu *et al.* 2002).

EOs (1.5-3.5 mg/l) extracted from clove leaves reduced respiration rate and brown index of apple, as well as maintained fruit firmness, TSS and TA. Adding $CaCl_2$ can improve the efficiency of phenolic and EOs, which will be developed into potential preservative for fruit storage (Li *et al.* 2006).

When cherry fruit quality parameters were determined, those treated (99.5% purity) with eugenol, thymol or menthol showed benefits in terms of reduced weight loss, delayed colour changes and maintenance of fruit firmness compared with control. Stem remained green in treated cherries while they became brown in control. However, cherries packaged with eucalyptol behaved even worse than control cherries, with generation of off-flavours, loss of quality and stem browning (Serrano *et al.* 2005).

Treatment with 0.16% (v/v) of basil or lemongrass oil prolonged fruit storage of bananas without any detrimental effect on their organoleptic properties (Anthony *et al.* 2003). Similar, treated banana with cinnamon oil (0.16-0.22 % v/v) and clove oil (0.02 % v/v) did not affect the organoleptic and physico-chemical properties of fruit (Ranasinghe *et al.* 2005). However, oil of Ceylon citronella (*Cymbopogon nardus* L.) improved fruit firmness but affected negatively the texture and the flavour of the banana fruit and reduced the overall acceptability (Anthony *et al.* 2003).

Dipping in 0.5 ml/l water solution of origanum oil had some effect on fungus growth in the kiwifruit flesh, but reduced fruit quality making them completely unuseful (Thanassopoulos and Yanna 1997). Moreover, carvacrol and cinnamic acid, reduced fruit quality (undesirable colour and odour) of fresh-cut kiwifruit at chilling temperatures (Roller and Seedhar 2002).

EOs of cassia (0.5 ml/l) alone or in combination with $MgSO_4$ (0.25-3% w/v) had no adverse effect on cherry tomatoes quality-related characteristics (fruit firmness, ascorbic acid content, TSS, TA, fruit colour) (Feng *et al.* 2008). Tomato fruit exposed to cinnamon volatile oil compounds (0.05-0.5 ml/l) and storage at 13°C during or following vapour exposure maintained fruit firmness and stimulated levels of TSS only as long as exposure took place. However, no differences observed for percentage weight loss, organic acid content, sweetness and total phenolic content when tomatoes exposed to cinnamon or eucalyptus oil (Tzortzakis 2007b). Taste panel was carried out in a tomato paste and sample with 0.5 ml/l thyme oil was accepted by panelists. However, samples with 0.5 ml/l of summer savory and clove oil scored less for odor and taste compared with control (Omidbeygi *et al.* 2007).

When Fungastop™ sprayed on lettuce resulted in lower weight loss and reduction in ethylene production and respiration rates were observed in both Fungastop™ and chemical treated lettuces than found in controls. However, no differences observed for TSS, TA, firmness and colour among treatments. There was a similar increase in lettuce shelf-life for both treatments compared to the controls, and thus the natural fungicide might be a good alternative to the use of synthetic fungicides, and in turn to fulfill consumer requirements for more natural and healthy foods (Martınez-Romero *et al.* 2008). Moreover, the acceptability to a sensory panel of lettuce treated with oregano at 0.25 ml/l varies but no differences determined between oregano-treated lettuce and that washed with chlorinated water considering gas composition, color, texture and water activity of samples (Gutierrez *et al.* 2008, 2009). However, greater thyme and lemon balm oil concentrations (up to 1.0 ml/l) rejected by panelists as they perceived strong chemical odors from these samples (Gutierrez *et al.* 2008).

Carrot-treated with EOs of oregano (0.25 ml/l) or oregano and thyme (0.15 ml/l and 0.25 ml/l respectively) had no differences on gas composition, color, texture and water activity of samples compared with samples washed with chlorinated water (Gutierrez *et al.* 2009). The sensory panel found EO treatments acceptable for carrots throughout storage. Correlating microbial and sensory changes with volatile emissions identified 12 volatile quality markers. As a consequence, oregano might be a suitable decontamination alternative to chlorine for ready-to-eat carrots, while the identification of volatile quality markers useful complement to sensory and microbiological assessments in the monitoring of organoleptic property changes and shelf-life of fresh vegetables (Gutierrez *et al.* 2009).

Preliminary research showed that mushrooms exposed to eucalyptus oil and packaged in a paper bag inside a plastic bag had a better overall appearance (whiter appearance and reduced weight loss) than those mushrooms not exposed to EOs (Jobling 2000).

Fumigated 'Crimson' table grape with thymol or menthol (0.5 ml/l) showed significant lower weight loss and TSS/TA ratio (indendifying swettness), than controls during storage, as well as delayed the colour changes and fruit firmness (Martinez-Romero *et al.* 2005). Ethylene and respiration rate (berry physiological parameters) increased drastically in control inoculated-grapes, while these increases were lower as higher were the carvacrol (0.05-1.0 ml/l) applied doses (Martínez-Romero *et al.* 2007). Active packaging was developed by adding eugenol or thymol (99.5% purity) to table grapes affected fruit quality parameters in terms of sensory, nutritional and functional properties. The addition of eugenol or thymol inside the packages significantly delayed the loss of firmness, delayed the change in maturity index (TSS/TA), increased glucose and fructose levels, and maintained levels of the ascorbic acid and total phenols (Valero *et al.* 2006).

Impacts of essential oil on fruit coating edible films

The increase in consumption of fresh-cut produce has resulted in frequent outbreaks of illness associated with raw fruits and vegetables. During minimal processing, spoilage and pathogenic microorganisms can gain access to the nutrients inside fruits and multiply (Thunberg *et al.* 2002). The presence of *E. coli* on the surface of fruits may adversely affect the safety of fresh and fresh-cut fruit. Controlling the numbers and the growth of pathogenic bacteria is a challenging problem for the food processing industry (Burt and Reinders 2003). The use of edible films and coatings for a wide range of food products, including fresh and minimally processed vegetables and fruits, has received increasing interest because films can serve as carriers for a wide range of food additives, including antimicrobials (Pranoto *et al.* 2005). Incorporating antimicrobial compounds into edible films or coatings provides a novel way to enhance the safety and shelf life of ready-to-eat foods (Cagri *et al.* 2001). EOs have been extensively evaluated for their abilities to protect food against pathogenic bacteria contaminating apple juice (Friedman *et al.* 2004b) and other foods (Burt 2004).

To assess the antimicrobial effectiveness of natural compounds and plant extracts, it has been previously evaluated the bactericidal activities of about 200 plant EOs,

oil compounds, phenolic compounds, and flavonoids against major foodborne pathogenic bacteria including antibiotic-resistant bacteria (Friedman *et al.* 2003, 2004a, 2004b). The physicochemical properties of edible films (color, tensile strength, water vapor, and oxygen permeability) relate to coating enhancement of the mechanical integrity of foods, inhibition of moisture loss and oxidative rancidity, and final-product appearance (Debeaufort *et al.* 1998). Combined analysis of antimicrobial and physicochemical properties is crucial for predicting the behavior of antimicrobial edible films (Cagri *et al.* 2001). Coating fruit with wax or polymers reduces fruit softening, chlorophyll degradation and chilling injury in fruit (Sornsrivichai *et al.* 1990; Hagenmaier and Shaw 1992; Saftner 1999). Ju *et al.* (2000c) indicated that the positive effects of plant oils on fruit quality attributes may relate to delayed ethylene production, although the mechanism by which plant oils inhibit ethylene production is not clear. The mechanism by which fruit coatings delay fruit senescence is explained primarily as a response to the modification of internal atmosphere, including CO_2, O_2, and ethylene (Saftner 1999) and warrants further investigation.

A chitosan/methyl cellulose film incorporating vanillin (4-hydroxy-3-methoxybenzaldehyde) is the major constituent of vanilla beans) as a natural antimicrobial agent provided an inhibitory effect against *E. coli* and *S. cerevisiae* on fresh-cut cantaloupe (*Cucumis melo cantalupensis* L.) and pineapple (*Ananas comosus* L.) (Sangsuwana *et al.* 2008). Vanillin has been used to inhibit *E. coli* O157:H7 and *L. monocytogenes* in 'Granny Smith' apple juice (Moon *et al.* 2006). Rupasinghe *et al.* (2006) reported that total aerobic counts of fresh-cut apple slices decreased from 4.3 log CFU/g fresh weight (untreated) to 1.6 log/CFU by using NatureSeal (an antibrowning agent) plus 12mM vanillin after 19 days at 4°C. Cerrutti *et al.* (1997) treated strawberry puree with a mild heat treatment combined with 3000 mg/l vanillin and 500 mg/l ascorbic acid. They found that the inhibition of native and inoculated flora growth for at least 60 days storage at room temperature. Penney *et al.* (2004) found that vanillin at 2000 mg/l suppressed fungal and total microbial growth in yoghurt significantly over the 3-week period. Pranoto *et al.* (2005) incorporated garlic oil (0.1 ml of garlic oil/g) in chitosan film, found antimicrobial activity against *S. aureus*, *L. monocytogenes*, and *Bacillus cereus*. Plant-derived EOs can be used to prepare apple-based antimicrobial edible films for various food applications. Edible films, as carriers of antimicrobial compounds, constitute an approach for incorporating plant EOs (oregano, cinnamon, and lemongrass oils) onto fresh-cut fruit surfaces providing bactericidal activities against *E. coli* (Rojas-Grau *et al.* 2006).

Edible films, as carriers of antimicrobial compounds, constitute an approach for incorporating plant EOs onto fresh-cut fruit surfaces. Oregano, cinnamon, lemongrass and vanillin oils (0.05-1.5% w/w) in apple puree film-forming solution (APFFS) and in an edible film made from the apple puree solution (APEF) revealed antibacterial activity against *E. coli* and *Listeria innocua* (Rojas-Grau *et al.* 2006, 2007). Coated apples containing high concentrations (up to 1.5% w/w) of EOs (oregano, cinnamon, lemongrass and vanillin) following packing with polypropylene film revealed significant reduction in the rates of ethylene production and respiration rates while lemongrass containing coatings induced severe texture softening (Rojas-Grau *et al.* 2007).

Effects of cinnamon EOs and its mixture with chitosan and calcium chloride on the storage of 'Dangshan' pear (*Pyrus communis* L.) were investigated at low temperature (0-2°C) combined with coating treatment (Gou *et al*. 2008). The results showed that cinnamon EOs (0.06 ml/l) and its mixture with chitosan (1%) and calcium chloride (1%) improved fruit taste and flavor, delayed the appearance of fruit respiration peak for 10 days and restrain the increase of MDA content, relative electric conductivity and polyphenoloxidase activity. Compared with the control, at storage of 40 days, superoxide dismutase and catalase activity were increased by 239 and 146%, but peroxidase activity is decreased by 56% (Gou *et al.* 2008). Plant (soybean (*Glycine max* L.), corn (Zea maize L.), peanut (*Arachis hypogaea* L.), cottonseed (*Gossypium* sp.) and linseed (*Linum usitatissimum* L.)) oil emulsions (3, 6, and 9%) applied at harvest and stored at 0°C for 6 months, improved fruit quality of pears (cv. 'Laiyang Chili' and 'Ya Li') (Ju *et al.* 2000c). Plant oil emulsions, regardless of the sources of oil, at 9% concentration, delayed ethylene production and respiration, maintained fruit quality attributes, such as firmness, color, TSS and TA, and controlled internal browning, completely after 6 months storage. No off-flavor was detected in either oil-treated and control fruit by sensory evaluation (Ju *et al.* 2000c). When applied at harvest, plant oils (corn, soybean, peanut, olive (*Olea europaea* L.), cottonseed, and linseed) delay climacteric rise in ethylene and ripening and maintained fruit quality attributes in 'Golden Delicious' apples and 'Bartlett' pears (Ju *et al.* 2000b) and inhibit scald development and degreening in 'Delicious' apples (Ju *et al.* 2000a) during and after prolonged cold storage. Similarly, coating fruit with wax or polymers also reduces fruit softening and chlorophyll degradation (Sornsrivichai *et al.* 1990; Saftner 1999). The other reason for coating fruit with wax or polymers is to reduce chilling injury in fruit (Hagenmaier and Shaw 1992). The mechanism by which fruit coatings delay fruit senescence is explained primarily as a response to the modification of internal atmosphere, including CO_2, O_2, and ethylene but warrants further investigation (Saftner 1999).

EOs (cinnamon, palmarosa and lemongrass) and their main active compounds (eugenol, geraniol, citral) incorporated into an alginate-based edible coating on fresh-cut melon reduced respiration rates and that result was a direct consequence of the inhibition of the native microflora growth achieved with the use of that specific coating. However, some fresh-cut melon characteristics were affected such as firmness and color causing a reduction of physicochemical shelf-life. According to the results, palmarosa oil incorporated at 0.3% into the coating appear to be a promising preservation alternative for fresh-cut melon, since it had a good acceptation by panellists, maintained the fruit quality parameters, inhibited the native flora growth and reduced *S. enteritidis* population (Raybaudi-Massilia *et al.* 2008). Vanillin film coating reduced the ascorbic acid content, increased the intensity of yellow color of pineapple as well as pineapple removed from stretch film had higher respiration rates and ethanol contents than other treatments (Sangsuwana *et al.* 2008).

LEGAL ASPECTS AND SAFETY OF THE USE OF ESSENTIAL OILS AND THEIR COMPONENTS IN FOODS

A number of EO components have been registered by the European Commission for use as flavourings in foodstuffs. The flavourings registered are considered to present no risk to the health of the consumer and include amongst others carvacrol, carvone, cinnamaldehyde, citral, *p*-cymene, eugenol, limonene, menthol and thymol. New flavourings may only be evaluated for registration after toxicological and metabolic studies have been carried out (as reviewed by Burt 2004), which could entail a considerable financial outlay.

In spite of the fact that a considerable number of EO components are GRAS and/or approved food flavourings, some research data indicate irritation and toxicity. For example, eugenol, menthol and thymol, when applied in root canal treatments, have been known to cause irritation of mouth tissues. The results of a cytotoxicity study on these compounds suggest that gum irritation may be related to membrane lysis and surface activity and that tissue penetration may be related at least partly to membrane affinity and lipid solubility (Manabe *et al.* 1987). Some EOs and their components have been known to cause allergic contact

dermatitis in people who use them frequently (Burt 2004). It is recommended that more safety studies be carried out before EOs are more widely used or at greater concentrations in foods that at present.

FUTURE WORK

There is a need to better understand how EOs components and other natural antimicrobials interact with cells to cause antifungal and bacteriostatic or bactericidal effects and the putative changes in membrane. Experimental tests could be used to develop new approaches for increasing the sensitivity of these and other more troublesome organisms in foods by taking advantage of synergies among the antimicrobials. Further work along these lines should allow better understanding of the basis for microbial species resistance or sensitivity. However, the extent to which bacteria can adapt to the presence of EOs in foods is also important for further evaluation; *B. cereus* has been shown to become less sensitive to carvacrol after being grown in the presence of nonlethal concentrations (Ultee *et al.* 2000). Antagonism between EO and food ingredients is undesirable and research is needed so it can be avoided in practical applications. The stability of EOs during food processing will also need to be studied. Interactions between EOs and their components and other food ingredients and food additives as well as fresh produce organoleptic properties, need to be investigated. Clove and oregano oils canacquire a dark pigmentation when in contact with iron (Bauer *et al.* 2001); this may impose limitations on their application. Synergistic effects could be exploited so as to maximise the antibacterial activity of EOs and to minimise the concentrations required to achieve a particular antibacterial effect.

CONCLUSION

The use of EOs in consumer goods is expected to increase in the future due to the rise of 'green consumerism', which stimulates the use and development of products derived from plants (De Silva 1996). This applies to the food and cosmetic sectors but also to medicinal products. Undesirable organoleptic effects can be limited by careful selection of EO according to the type of food. Synergism and antagonism between components of EOs and food constituents require more study before these substances can be reliably used in commercial applications. If the active substances are to be added to foods in greater concentrations than is currently normal practice for flavourings, further safety studies may be necessary. Several research studies took place by now; however, more focus needed on fresh produce preservation and quality related characteristics, prolonging fruit storage as well as enhance defense mechanism of fresh produce.

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