Essential Oils and Their Principal Constituents as Antimicrobial Agents for Synthetic Packaging Films

Kuorwel, Kuorwel Kuai, Cran, Marlene, Sonneveld, Kees, Miltz, Joseph and Bigger, Stephen W (2011) Essential Oils and Their Principal Constituents as Antimicrobial Agents for Synthetic Packaging Films. Journal of Food Science, 76 (9). R164-R177. ISSN 0022-1147 (print) 1750-3841 (online)

Essential Oils and Their Principal Constituents as Antimicrobial Agents for Synthetic Packaging Films

Kuorwel K. Kuorwel[1], Marlene J. Cran[2], Kees Sonneveld[3],

Joseph Miltz[4] and Stephen W. Bigger[1*]

1. School of Engineering and Science, 2. Institute for Sustainability and Innovation

Victoria University, PO Box 14428, Melbourne, 8001, Australia.

3. KS PackExpert & Associates, PO Box 399, Mansfield, 3724, Australia

4. Department of Biotechnology and Food Engineering, Technion-Israel Institute of Technology, Haifa, 3200, Israel

***Corresponding Author**

Prof. Stephen W. Bigger

School of Engineering and Science, Victoria University,

PO Box 14428, Melbourne, 8001, Australia

Tel: +61 3 9919 2959

Fax: +61 3 9919 2005

E-mail: stephen.bigger@vu.edu.au

Short version of title: AM Agents Used in Synthetic Films (. . .)

Choice of journal section: Concise Reviews and Hypotheses in Food Science

Word Count: 12606

Abstract

Spices and herbal plant species have been recognized to possess a broad spectrum of active constituents that exhibit antimicrobial (AM) activity. These active compounds are produced as secondary metabolites associated with the volatile essential oil (EO) fraction of these plants. A wide range of AM agents derived from EOs have the potential to be used in AM packaging systems which is one of the promising forms of active packaging systems aimed at protecting food products from microbial contamination. Many studies have evaluated the AM activity of synthetic AM and/or natural AM agents incorporated into packaging materials and have demonstrated effective AM activity by controlling the growth of microorganisms. This review examines the more common synthetic and natural AM agents incorporated into or coated onto synthetic packaging films for AM packaging applications. The focus is on the widely studied herb varieties including basil, oregano and thyme and their essential oils.

Keywords: Essential oils, natural AM agents, active packaging, antimicrobial packaging, microbial contamination

1 Introduction

Food products can be subjected to microbial contamination that is mainly caused by bacteria, yeasts and fungi. Many of these microorganisms can cause undesirable reactions that deteriorate the flavour, odour, colour, sensory, and textual properties of foods (Appendini and Hotchkiss 1997; Vermeiren and others 1999; Weng and others 1999; Appendini and Hotchkiss 2002; Vermeiren and others 2002; Devlieghere and others 2004a; Han 2005; Rupika and others 2005; Davidson and Taylor 2007; Gutierrez and others 2008). Microbial growth in food products is a major concern because some microorganisms can potentially cause food-borne illness (Padgett and others 1998; Natrajan and Sheldon 2000; Cha and Chinnan 2004; Davidson and others 2005; de Oliveira and others 2007). In packaged foods, the growth and survival of common spoilage and pathogenic microorganisms such as *Listeria monocytogenes*, *Escherichia coli* O157, *Salmonella*, *Staphylococcus aureus*, *Bacillus cereus*, *Campylobacter*, *Clostridium perfringens, Aspergillus niger* and *Saccharomyce cerevisiae* are affected by a variety of intrinsic factors such as pH, water activity, and the presence of oxygen or by extrinsic factors associated with storage conditions including temperature, time and relative humidity (Singh and others 2003; López-Malo and others 2005; Rydlo and others 2006). Many food products including various types of cheeses, meats, poultry and baked products are highly susceptible to microbial spoilage (Weng and Hotchkiss 1993; Suppakul 2004; Limjaroen and others 2005; Schelz and others 2006; Silveira and others 2007).

To prevent the growth of spoilage and pathogenic microorganisms on foods, various traditional preservation techniques such as heat treatment, salting, acidification and drying are used in the food industry (Quintavalla and Vicini 2002; Ozdemir and Floros 2004; Davidson and Taylor 2007; Farkas 2007). In recent years, a rise in consumer demand for safe, fresh and minimally-processed foods, has led to the development of new preservation

techniques. Active packaging (AP) technologies, for example, can provide safe food products with longer shelf lives (Rooney 1995; Lau and Wong 2000; Vermeiren and others 2002; Fitzgerald and others 2003; Ozdemir and Floros 2004; Gutierrez and others 2008). In the food industry, spoilage of food products, including spoilage that is caused by microorganisms is a major concern. The AP technologies designed primarily to protect food products from deterioration and from the growth of microorganisms can involve the use of synthetic or natural antimicrobial (AM) agents (Juneja and Sofos 2005). To diminish food spoilage by microorganisms, different AM agents (primarily synthetic) are commonly incorporated directly into the food. This method has many disadvantages: (i) consumers prefer foods with no or minimal synthetic additives because of concerns about side-effects; (ii) since food spoilage occurs primarily on the surface, incorporation of relatively large quantities of the agents in the bulk of the food is not justified; (iii) some of the synthetic agents possess a distinct flavour that may rendered the food flavour, and (iv) synthetic additives have to be declared on the package. Therefore, packaging materials that incorporate in them the AM agent as an additional protective barrier are emerging as the preferred preservation method. Several authors have reported AP technologies that involve the use of films produced from synthetic polymers (Miltz and others 1995; Rooney 1995; Smith and others 1995). These materials can act as carriers for active agents, including AM compounds, in order to maintain high concentrations of the agent on or near the food surface to control or prevent the growth of spoilage and pathogenic microorganisms (Krochta and De Mulder-Johnston 1997; Joerger 2007; Raybaudi-Massilia and others 2009; Rojas-Graü and others 2009; Suppakul and others 2011a). Thus a packaging film impregnated or coated with an AM agent could potentially extend the shelf life and improve the microbial safety of food products (Appendini and Hotchkiss 2002; Suppakul and others 2003b; Burt 2004; Kuorwel and others 2011b).

Although AM agents such as essential oils (EOs) and/or their principal components may exhibit AM activity against various microorganisms when incorporated into packaging materials, the organoleptic properties of the packaged food products are one of the important factors that must also be taken into consideration. According to Davison and Zivanovic (2003), the concentration of AM agents required to demonstrate AM activity against various microorganisms on food products might be higher than the concentration applied for flavouring purposes. As a result, this might cause food tainting and/or adverse sensorial effects to food products (Smith-Palmer and others 2001; Bagamboula and others 2004). The adverse sensorial effects of AM agents to food products can be overcome by masking the odor of AM agents with other approved aroma compound as suggested by Gutiérrez and others (2009). An understanding of the relationship between minimum inhibitory concentration and acceptable organoleptic properties of AM Agents such as EOs and/or their constituents is also important (Lambert and others 2001). In some cases, the replacement of EOs with one or a number of their principal constituents may provide equal AM effectiveness but with milder flavouring attributes (Lambert and others 2001; Smith-Palmer and others 2001).

In a recent review, the current authors presented an evaluation of the AM activity of biodegradable polysaccharide and protein based films containing natural agents (Kuorwel and others 2011b). These films showed the potential for wide-range of applications in food packaging where undesirable microbial growth is a concern. Moreover, these films degrade readily in the environment but the acquisition of this attribute may harm the processability and mechanical stability of the film. Thus, in spite of the increasing concern in recent years about the use of synthetic polymers due to their poor biodegradability, these materials have several advantages including low cost, good processability and sound mechanical and

physical properties. Therefore, development of AM packaging materials manufactured from synthetic polymers such as low-density polyethylene (LDPE), high-density polyethylene (HDPE), polystyrene (PS), polyethylene terephthalate (PET) and polypropylene (PP) is still important in offering commercial benefits for packaging food products. In the current review, a detailed summary of synthetic films utilising common synthetic and natural AM agents is presented with an emphasis on the principal components of basil, oregano, and thyme essential oils (EOs) namely, linalool, carvacrol and thymol respectively. This is followed by a list of other natural AM agents that have the potential for controlling microbial growth on foods.

2 Antimicrobial Packaging Systems

Studies have shown that AM packaging systems can increase the shelf life of packaged foods by extending the lag phase and reducing the growth rate of spoilage microorganisms (Han 2000; Cooksey 2001; Appendini and Hotchkiss 2002; Rydlo and others 2006; Coma 2007; de Oliveira and others 2007; Gutierrez and others 2008; Rardniyom and others 2008; Rupika and others 2008). In the past, preservatives were directly added into food products to protect them from microbial contamination. This process of direct addition of preservatives into foods may result in levels of additives in excess to those required for an efficient AM effect. New AM packaging systems have attracted much attention in the food industry with the aim of replacing the conventional food preservation systems (Weng and Hotchkiss 1993; An and others 1998; Quintavalla and Vicini 2002; Bagamboula and others 2004; Devlieghere and others 2004b; Miltz and others 2006).

An AM packaging system can be produced by: directly incorporating AM agents into packaging films; coating of the packaging films with AM agents; developing packaging

materials from polymers that have inherent AM properties (Vermeiren and others 2002; Suppakul and others 2003b). Typically, AM packaging systems can be regarded as migrating or non-migrating with the distinction depending on the specific AM agent used and on its interactions with the packaging and food matrix (Cooksey 2000). In a migrating system, the AM agent is released from the packaging film into the package headspace and onto the food surface and such systems are most useful when direct contact between the packaging film and food product is not required for efficient AM activity (Weng and Hotchkiss 1993; Cooksey 2000). The non-migrating systems involve packaging materials in which the AM agent is immobilised within the material (Brody and others 2001) and these systems can be applied where direct contact between the food and the material can be achieved or is required for effective AM activity (Vermeiren and others 2002; Suppakul and others 2003b). In either AM packaging system, both synthetic and natural AM agents can be incorporated into or coated onto the packaging material. The mode of action of AM agents incorporated in a packaging material is influenced by the controlled and slow release of the agent onto the food surfaces. This is required in order to maintain an adequate concentration of the agent on the food and effectively inhibit microbial growth throughout the product shelf life (Cooksey 2005; Salleh and others 2007; Cran and others 2010; Tunç and Duman 2011). Han (2005) suggested that the mass transfer rate of an AM agent should not be faster than the growth rate of the target microorganism, otherwise the AM agent might be diluted on the surface of the packaged food product, thus limiting the AM activity.

During extrusion or compression moulding of AM films, the temperature and mechanical energy input, such as shearing forces, must be carefully considered (Han 2003). High-processing temperatures, for example, may result in considerable losses of volatile AM agents (Han and Floros 1997; Han 2000; Rupika and others 2005; Suppakul and others

2011b). Moreover, Cooksey (2005) suggested that an AM agent might partly or completely lose its AM activity if incorporated into a film under harsh processing conditions. Therefore, to minimise the loss of AM agent during processing, temperatures that are as low as possible should be applied (Han and Floros 1998; Suppakul and others 2011b). The storage temperature may also influence the activity of AM agents that are incorporated into packaging films (Vojdani and Torres 1989; Han 2005). The concentration of AM agents retained in the film may decrease during long-term storage. However, the amount of AM agent retained in the film after a long storage period may be sufficient to demonstrate AM activity as shown by Suppakul and others (2011b). Du and others (2008) reported AM activity against *E. coli* (using an agar disc diffusion method) of carvacrol incorporated into films for edible apples that were stored for 7 weeks.

2.1 Synthetic AM Agents

In the past few decades, various synthetic AM agents have been investigated and developed into food packaging materials (Weng and Hotchkiss 1992; Weng and Hotchkiss 1993). Many of these agents including various organic acids and salts have been approved by regulatory agencies and have since been used for the preservation of food products (Davidson and Taylor 2007). Synthetic AM agents that have demonstrated inhibitory activity against different microorganisms include sodium benzoates and propionates, potassium sorbates, sulfites, chlorides, nitrites, triclosan, fungicides (e.g. benomyl, imazalil) and various metal ions including silver zeolites, quaternary ammonium salts and copper ions (Chen and others 1996; Devlieghere and others 2000a; Han 2000; Ouattara and others 2000; Hoffman and others 2001; Cooksey 2005). Other AM agents such as acetic acid from vinegar and benzoic acid from cranberries are found in nature, but are classified as synthetic AM agents when produced synthetically (Davidson and Taylor 2007).

Many synthetic AM compounds have been evaluated in synthetic polymeric materials by various researchers. Table 1 summarises these synthetic AM agents incorporated into or coated onto packaging materials as potential candidates for food packaging. Although Table 1 contains a large amount of information on the activity of AM agents successfully incorporated into various synthetic polymers, comparison between the different AM agents and/or AM films is difficult due to variations in strains of microorganisms and different experimental conditions or equipment used by the various researchers. In order to compare the results of various experiments involving AM agents, there is a need for a standardisation of the test methods as suggested by Suppakul and others (2003a).

Numerous studies have concentrated on incorporating common food preservatives such as organic acids, their salts and anhydrides into packaging films (see Table 1). Studies on benzoic or sorbic acid incorporated into packaging materials have evaluated their action against various microorganisms in laboratory media such as agar plates and/or in actual food products. The packaging films incorporated with these organic acids or anhydrides have demonstrated inhibitory effects against various spoilage and pathogenic microorganisms. Weng and others (1999) showed that benzoic acid or sorbic acid incorporated into poly(ethylene-co-methacrylic acid) (PEMA) film inhibited the growth of *A. niger* and *Penicillium* sp. on solid media. Weng and Chen (1997) investigated the AM activity of benzoic acid or benzoyl chloride incorporated into ionomer films. The AM activity of these films was demonstrated by their ability to inhibit the growth of *Penicillium* sp. and *A. niger*. In an earlier study, Weng and Hotchkiss (1993) incorporated benzoic acid or benzoic anhydride into LDPE films which significantly suppressed the growth of *Rhizopus stolonifer*, *Penicillium* sp. and *A. toxacarius* on potato dextrose agar and on the surface of Cheddar cheese. Matche and others (2006) examined the AM activity of benzoyl chloride incorporated

into modified ethylene acrylic acid films against *Penicillum* sp. and *A. niger* sp. on solid media for 15 days with the film demonstrating inhibition against both species. Silveira and others (2007) incorporated sorbic acid into LDPE films with the aim of preserving fresh pastry dough. It was found that 3% (w/w) sorbic acid incorporated into a 70 μm film reduced 2 and 1.5 log cycles of mesophilic and psychrotrophic bacteria respectively on the pastry dough after 40 days of storage at 8°C compared to the control film. Limjaroen and others (2005) coated sorbic acid onto polyvinylidene chloride copolymer films to control the growth of *L. monocytogenes* on beef bologna and Cheddar cheese. It was found that sorbic acid coated on the films inhibited microbial growth on cheese by log 0.6 $CFUg^{-1}$ after 28 days of storage at 4°C. They further reported that the population of *L. monocytogenes* on beef bologna was reduced by log 0.6 and 1.4 $CFUg^{-1}$ for films containing 1.5% and 3.0% (w/v) respectively compared to the control film.

Other researchers have studied the AM activity of salts against several microorganisms as shown in Table 1. Han and Flores (1997) developed LDPE films containing potassium sorbate and found that these films successfully reduced the growth of *S. cerevisiae in vitro* experiments. Vartiainen and others (2003b) demonstrated that potassium sorbate, sodium benzoate and sodium nitrate incorporated into LDPE, poly(maleic acid-co-olefine), PET or PS films inhibited the growth of *B. cereus* on culture media. Limjaroen and others (2003) coated potassium sorbate onto polyvinylidene chloride copolymer films and reported that the films inhibited the growth of *L. monocytogenes* on solid media.

In addition to the antibacterial activity, the antifungal activity of synthetic AM agents incorporated in polymeric materials has been investigated (Halek and Anita 1989; López-Malo and others 2007). Vartiainen and others (2003a) examined the inhibitory effects of

imazalil incorporated into LDPE against the growth of *A. niger* by the agar diffusion assay with films containing 0.05-0.25% (w/w) imazalil demonstrating significant inhibitory activity. Weng and Hotchkiss (1992) incorporated imazalil into LDPE film and evaluated the antimycotic activity of this agent on the growth of *A. toxacarius* and *Penicillium* sp. on potato dextrose agar (PDA) and Cheddar cheese. They reported that 2 g kg^{-1} of imazalil suppressed the growth of *A. toxacarius* on PDA whereas a film containing 1 g kg^{-1} of imazalil reduced the growth of *Penicillium* sp. The latter film inhibited the growth of both mould species on the surface of Cheddar cheese. López-Malo and others (2002; 2005) examined the antifungal activity of potassium sorbate, sodium benzoate and sodium bisulfite against the growth of *Aspergillus flavus* inoculated on laboratory media with each of the agents imparting an inhibitory effect. López-Malo and others (2007) investigated the antifungal activity of sodium benzoate and cinnamon extract, separately or in combination, against the growth of *A. flavus* on potato dextrose agar or a checkerboard array respectively. They found that both AM agents demonstrated antifungal activity on *A. flavus*, with cinnamon extract being more effective than sodium benzoate. They claimed that mixtures of cinnamon extract and sodium benzoate showed promising antifungal activity.

Triclosan and hexamethylenetetramine are common synthetic AM agents that have been evaluated in packaging systems with some commercial developments. Vermeiren and others (2002) investigated the AM activity of triclosan incorporated into LDPE film and reported that concentrations of 0.5 and 1.0% (w/w) demonstrated AM activity against *L. monocytogenes, Sal. enteritidis, Staph. aureus, E. coli* O157:H7 and *Brocothrix thermosphacta* in an agar diffusion assay. Cutter (1999) reported that triclosan was effective against bacteria on the surface of beef. Recently, Camilloto and others (2010) studied the activity of triclosan incorporated into LDPE against *Staph. aureus*, *E. coli*, *L. innocua* and *P.*

aeruginosa in the agar disc diffusion test and found that the AM film inhibited the growth of *Staph. aureus* and *E. coli*. Chung and others (2003a) investigated the AM activity of triclosan coated onto styrene-acrylate copolymer against *Enterococcus faecalis* on solid and in liquid media and showed effective inhibition of the bacteria. Ji and Zhang (2009) reported that triclosan incorporated into PVC film inhibited the growth of *Staph. aureus* and *E. coli* using the plate-counting technique. Devlieghere and others (2000b) studied the AM activity of hexamethylenetetramine impregnated into an LDPE film and found it to be effective against spoilage microorganisms on cooked ham.

2.2 Natural Antimicrobial Agents

In recent years, natural AM agents have attracted much attention in the food and packaging industries as a replacement for synthetic ones for food preservation. According to Davidson and Zivanovic (Davidson and Zivanovic 2003), natural AM agents are classified by their sources: AM agents derived from plant EOs (e.g. basil, thyme, oregano, cinnamon, clove and rosemary); animal sources (e.g. lysozyme, lactoferrin); microbial sources (nisin, natamycin); and naturally occurring polymers (chitosan). The EOs extracted from plant sources consist of various mixtures including terpenoids, esters, aldehydes, ketones, acids and alcohols (Dorman and Deans 2000). These plant EOs are volatile and generally possess relatively strong odours (Bakkali and others 2008).

Extracts derived from various herbs and EOs contain a range of natural compounds such as thymol, linalool and carvacrol which have a broad AM spectrum against different pathogenic and spoilage microorganisms including Gram-negative species such as *E. coli, Yersinia enterocolitica, P. aeruginosa* and *Sal. choleraesuis* (López and others 2007a; Suppakul and others 2011b), Gram-positive bacteria such as *L. monocytogenes, Staph. aureus, B.* cereus

(Friedman and others 2002; López and others 2007b; Gutiérrez and others 2009), yeasts such as *S. cerevisiae, Candida albicans, Debaryomyces hansenii* (Rupika and others 2006; Suppakul and others 2008; Kuorwel and others 2011a) and moulds such as *Alternaria alternate, A. niger, Botrytis cinerae, A. flavus, penicllium roqueforti* (López-Malo and others 2007; Rodríguez-Lafuente and others 2010). These additives are considered to be safe and have the "Generally Recognised As Safe" (GRAS) status as designated by the American Food and Drug Administration (Zaika 1988; Han 2005; Matan and others 2006). Antimicrobial agents derived from plant sources are produced as secondary metabolites and are associated generally with the volatile EO fractions. The mode of action of AM agents and/or AM activity of plant EOs is related to their chemical structure namely, the presence of hydrophilic functional groups such as the hydroxyl groups of phenolic components and/or lipophilicity of the components in the EOs which depends on their concentration (Farag and others 1989; Davidson and Naidu 2000; Dorman and Deans 2000; Friedman and others 2002; Bagamboula and others 2004). Essential oils and their principal constituents inhibit microorganisms *via* a range of mechanisms such as: disruption of the cyctoplasmic membrane (Knobloch and others 1989; Sikkema and others 1995; Helander and others 1998); leakage of intracellular constituents such as metabolites and ions (Sikkema and others 1995; Lambert and others 2001); coagulation of cell content (Gustafson and others 1998; Pauli 2001); inhibition of protein synthesis (Helander and others 1998), enzymes associated with cell wall synthesis (Conner and Beuchat 1984), DNA/RNA synthesis (Ultee and others 1999; Tassou and others 2000), general/metabolite pathways (Ultee and others 2002); and/or the destruction of the osmotic integrity of the cell membrane (Ultee and Smid 2001). The AM activity of different EOs is very difficult to compare given the variation of EOs compositions amongst the plant species, differences in the geographic origin of the plants, harvesting

316 season, extraction methods and the part of plant that is used (Zaika 1988; Elgayyar and others
317 2001).
318 There are a number of test methods used to determine the AM activity of various EOs and
319 their principal constituents. These include diffusion methods (agar diffusion), dilution
320 methods (broth and agar dilution) and microatmosphere methods (Davidson and Zivanovic
321 2003; Guynot and others 2003; Nedorostova and others 2011; Tunç and Duman 2011). These
322 test methods provide preliminary information on the possible effectiveness of the tested
323 active constituents. The agar diffusion method has been widely used in the past, but the
324 results obtained from this technique are qualitative. Although the agar diffusion method can
325 indicate the AM activity of EOs and/or their principal components on solid media, the high
326 hydrophobicity of EOs is always a major problem (Davidson and Zivanovic 2003). As a
327 result, the agar disc diffusion assays do not generally demonstrate a clear zone of inhibition at
328 very low concentrations; however these do exhibit a clear inhibition zone at high
329 concentrations of hydrophobic, lipophilic AM agents (Friedman and others 2002; Sanla-Ead
330 and others 2011). Conversely, microatmosphere methods, which allow the determination of
331 the AM activity of EOs and/or their constituents in the vapour phase, can be used with
332 lipophilic AM films at low concentrations of AM agents (López and others 2007a; Fisher and
333 others 2009; Goñi and others 2009; Kloucek and others 2011). Recently, Sanla-Ead and
334 others (2011) investigated the AM activity of cinnamaldehyde and eugenol incorporated into
335 cellulose-based packaging films against Gram-negative bacteria (*E. coli*, *Sal. enteritidis*),
336 Gram-positive bacteria (*L. monocytogenes*, *Staph. aureus*) and yeasts (*C. albicans*, *C.*
337 *cerevisiae)* using the vapour diffusion assay. The authors reported that cinnamaldehyde and
338 eugenol incorporated into cellulose-based packaging films demonstrated positive inhibitory
339 effects against the tested microorganisms.
340

Table 2 summarises the AM activity of a range of common natural agents that have been incorporated into or coated onto synthetic packaging films. Table 2 also lists other studies that have evaluated the inhibitory effects of natural AM agents *in vitro* or directly on food products without incorporating them into packaging films.

2.2.1 Antimicrobial Activity of Basil Essential Oils

Basil EOs contain primarily linalool and methylchavicol as the active volatile components which are responsible for their AM activity (Simon and others 1990; Fyfe and others 1998; Wan and others 1998; Bezic and others 2003; Suppakul 2004). Many studies have evaluated the AM activity of basil EOs against various microorganisms both *in vitro* and on a range of food products as shown in Table 2. Prasad and others (1986) investigated the AM activity of the EOs of *O. basilicum* against various Gram-positive and Gram-negative bacteria with the oils shown to be more effective against Gram-positive bacteria including *Bacillus sacharolyticus, B. stearothermophilus, B. subtilis, B. thurengiensis, Micrococcus glutamicus* and *Sarcina lutea* than the Gram-negative ones. Lachowicz and others (1998) evaluated the AM effects of EOs of sweet basil against acid-tolerant food microflora. They reported greater inhibitory effects of the tested EOs against the Gram-positive bacteria *Bacillus* sp., *Staph. aureus* sp., *Micrococcus* sp., *Sarcina* sp., *Lactobacillus* sp. than against the Gram-negative bacteria *E. coli, Salmonella* sp., *Enterobacter* sp. and *Pseudomonas* sp. In contrast to these studies, Koga and others (1999) found that the Gram-positive bacteria were more resistant to basil EOs than the Gram-negative ones.

Various researchers have reported also the inhibitory effect of basil EOs against fungi. Rai and others (1999) evaluated the antifungal activity of the EOs of ten plant species (including *O. basilicum*) and reported that the EOs of basil were active against all *Fusarium* species

including *F. acuminatum, F. solani, F. pallidoroseum* and *F. chlamydosporum.* Conner and Beuchat (1984) reported positive AM activity of basil EOs against *Kloeckera apiculata* on solid media. Basilico and Basilico (1999) investigated the inhibitory effects of some EOs, including that of basil (*O. basilicum*), against the growth of *A. ochraceus* and subsequent ochratoxin A production. They reported that at a level of 1000 ppm, only basil EO decreased the fungal growth and the production of ochratoxin A for up to 7 days after which mould growth occurred.

2.2.2 Antimicrobial Activity of Linalool

Linalool has been reported to possess both fungistatic and antibacterial properties against a wide spectrum of microorganisms such as *Staph. aureus, L. innocua, E. coli, A. niger* and *S. cerevisiae* (Lachowicz and others 1998; Friedman and others 2002; Suppakul and others 2003a). As shown in Table 2, numerous studies have evaluated the AM activity of linalool incorporated into packaging films. For example, Suppakul and others (2006; 2008) reported that linalool incorporated into LDPE film exhibited inhibitory activity against the growth of *Staph. aureus, L. innocua, E. coli* and *S. cerevisiae* on culture media and on the surface of Cheddar cheese. Rardniyom (2008) investigated the AM activity of linalool coated onto LDPE and nylon films against the growth of *E. coli* and reported effective inhibitory activity in liquid culture and on Cheddar cheese. Rupika and others (2006) reported that linalool incorporated into LDPE films demonstrated significant inhibitory activity against the growth of *L. innocua* and *E. coli* both *in vitro* and on the surface of Cheddar cheese. Suppakul and others (2011b) reported that linalool and/or methylchavicol incorporated into LDPE films demonstrated inhibitory activity against the growth of *E. coli* on agar disc media.

The AM activity of linalool against several microorganisms has also been reported in studies conducted *in vitro* only. Kim and others (1995) investigated the AM activity of some EO components including linalool against five food-borne pathogens (*E. coli, E. coli* O157:H7, *Sal. typhimurium, L. monocytogenes and V. vulnificus*) and found a dose-related increase in the zone of inhibition against all tested strains except for *L. monocytogenes*. Mazzanti and others (1998) reported that linalool completely inhibited the growth of all yeasts (seven strains of *C. albicans, C. krusei* and *C. tropicalis*), *Staph. aureus* and *E. coli* using the agar disc diffusion method. Dorman and Deans (2000) investigated the antibacterial activity of 21 plant volatile oil components including linalool against 25 bacterial strains using the agar well diffusion method. It was reported in this study that linalool was an effective AM agent against a broad spectrum of 23 out of the 25 bacterial strains investigated.

2.2.3 Antimicrobial Activity of Oregano and Thyme Essential Oils

Oregano and thyme are popular culinary herbs with their EOs containing terpenoid compounds, mainly the monoterpenoid phenols of thymol (5-methyl-2-[1-methylethyl] phenol) and carvacrol (5-isopropyl-2-methyl phenol). These EOs have been claimed to demonstrate potential health benefits, antioxidant activity and AM properties (Nychas 1995; Baratta and others 1998; Youdim and Deans 2000; Olasupo and others 2004; Tepe and others 2004; Davidson and Taylor 2007). The AM activity of thyme and oregano EOs is primarily attributed to their major components thymol and carvacrol respectively (Farag and others 1989; Cosentino and others 1999; Davidson and Naidu 2000; Dorman and Deans 2000; Lambert and others 2001; Bagamboula and others 2004; Davidson and Taylor 2007).

The AM activity of oregano and thyme EOs against various microorganisms has been investigated on media and on a range of food products as summarised in Table 2. For

example, Lin and others (2004) evaluated the AM activity of phenolic compounds derived from oregano against *L. monocytogenes* on solid media, on beef and on fish products and reported that the extracts exhibited AM activity against *L. monocytogenes* in the agar diffusion assays. Friedman (2004) studied the antibacterial activity of ten different EOs including that of oregano against *E. coli* and *Sal. enterica* in apple juice. They reported that the selected EOs exhibited greater AM activity against *Sal. enterica* than *E. coli*.

The AM activity of oregano and thyme EOs was investigated in liquid culture and solid media against various microorganisms. Becerril and others (2007) investigated the AM activity of oregano EOs incorporated into a patented plastic packaging material against *E. coli* and *Staph. aureus*, using a "kill time" assay. The authors claimed that oregano EOs exhibited significant AM activity with a kill time of approximately 90 min for *E. coli* and 104 min for *Staph. aureus*. Marques and others (2008) studied the AM activity of three natural AM agents: oregano, garlic and chitosan against the growth of *Sal. enterica* in liquid culture at 10 and 20°C. They reported that all of the natural agents inhibited significantly the microbial growth at both temperatures with oregano demonstrating the highest inhibitory effects followed by garlic then chitosan. Rodriguez-Lafuente and others (2010) investigated the AM activity of oregano and cinnamon EOs incorporated into packaging-paper against *Alternaria alternata* using an *in vitro* antifungal assay. The authors reported that oregano and cinnamon EOs inhibited the growth of *A. alternata* on solid media.

Nielsen and Rios (2000) reported that oregano EOs exhibit an inhibitory activity against microorganisms commonly associated with bread spoilage. Tepe and others (2004) examined the AM activity of *Thymus eigii* EOs and its main constituents carvacrol, thymol and *p*-cymene against *B. catarrhalis*, *C. perfringens*, *B. cereus*, *Staph. aureus*, *S. pneumoniae*, *M.*

smegmatis and *P. aeruginosa in vitro* and found that these EOs demonstrate AM activity against the tested microorganisms. More recently, Gutierrez and others (2008) evaluated the synergistic effect of the EOs of thyme, oregano, lemon balm, marjoram, rosemary and sage against *B. cereus, E. coli, L. monocytogenes* and *P. aeruginosa* using the spot test on agar media. They reported a significant AM activity of oregano in combination with basil, thyme or marjoram against *B. cereus, E. coli* and *P. aeruginosa*. Similarly, Gutierrez and others (2009) determined the AM activity of the EOs of thyme, oregano, lemon balm and marjoram against *Enterobacter* sp., *Listeria* sp., *Lactobacillus* sp. and *Pseudomonas* sp. using foods based on lettuce, meat and milk. Their findings demonstrated that minimum inhibitory concentrations were significantly lower in lettuce and beef media than in tryptic soy broth and that oregano and thyme produced the most active EOs. Lopez and others (2007b) reported AM activity of oregano, cinnamon and clove EOs incorporated into PP or PE/EVOH against various Gram-negative bacteria (*E. coli, Y. enterocolitica, P. aeruginosa* and *Sal. choleraesuis*), Gram-positive bacteria (*L. monocytogenes, Staph. aureus, B. cereus* and *E. faecalis*), yeasts (*C. albicans, D. hansenii, Z. rouxii)* and moulds (*B. cinerae, A. flavus, E. repens, p. roqueforti, P. islandicum, P. commune, P. nalgiovensis*). Similarly, Lopez and others (2007a) reported AM activity of cinnamon, oregano and thyme EOs against various Gram-negative bacteria (*E. coli, Y. enterocolitica, P. aeruginosa* and *Sal. choleraesuis*), Gram-positive bacteria (*L. monocytogenes, Staph. aureus, B. cereus* and *E. faecalis*), yeasts (*C. albicans)* and moulds (*A. flavus, P. islandicum*). The main constituents: cinnamaldehyde, carvacrol and thymol also demonstrated inhibitory effect against *L. monocytogenes, Sal. choleraesuis, A. flavus* and *C. albicans* using a modified vapour diffusion test.

Sagdiç and Özcan (2003) investigated the AM activity of various EOs including oregano and thyme EOs against different microorganisms including *Bacillus amyloliquefaciens, B. cereus,*

Enterobacter aerogenes, E. coli, Sal. enteritidis, Staph. aureus and *Yersinia enterocolitica*. They reported that oregano was particularly effective against all bacteria during incubation. Oussalah and others (2006) studied the inhibitory effects of sixty different EOs including oregano and thyme against *Pseudomonas putida*. The results of their study showed that many EOs possess *in vitro* antibacterial activity against *P. putida* with oregano and thyme EOs demonstrating the highest AM activity. Viuda-Martos and others (2008) evaluated the effectiveness of the EOs of oregano, sage, clove, thyme, rosemary and cumin on the growth of various microorganisms including *Lactobacillus curvatus, Lactobacillus sakei, Staph. carnosus* and *Staph. xylosus*, *Enterobacter gergoviae* and *Enterobacter amnigenus*. They found that each of the EOs demonstrated inhibitory activity against all bacteria tested with oregano showing the highest AM activity and reported that the effects of thyme, sage and rosemary were concentration dependent. Baydar and others (2004) studied the antibacterial activity of EOs of thyme, oregano and savoury against various pathogenic bacteria including *B. cereus, E. coli* and *L. monocytogenes*. They reported positive AM activity against the tested bacteria and suggested that the inhibition may be attributed to the action of the components carvacrol, γ-terpinene and *p*-cymene (a constituent of cumin or thyme EOs). The results of these studies demonstrate that oregano and thyme EOs have the potential to be used as AM agents in the food industry for better preservation of quality, enhancement of safety and extension of shelf life. Nevertheless, additional information is required on the benefits of these EOs before considering them as potential candidates for manufacturing of AM films with commercial applications.

2.2.4 Antimicrobial Efficacy of Carvacrol and Thymol

Carvacrol and thymol are the major components of oregano and thyme EOs. They have received substantial attention as useful natural AM agents due to their natural origin and

GRAS status, as well as them exhibiting a broad AM spectrum against different microorganisms, and possessing heat stability when incorporated into packaging materials (Deans and Ritchie 1987; Zaika 1988; Ultee and others 1998; Lorenzo and others 2003; Couladis and others 2004; Azaz and others 2005; Han 2005; Matan and others 2006). Table 2 shows that carvacrol and/or thymol can be applied in food products to control microbial contamination by various microorganisms including bacteria, yeasts and moulds.

Bagamboula and others (2004) determined the AM effect of carvacrol or thymol against *Shigella* sp. (*S. sonnei* and *S. flexneri*) on lettuce. They observed a decrease in *Shigella* sp. after washing the lettuce with 0.5% and 1% (v/v) thymol or carvacrol and found that at 1% (v/v) of each agent, the population decreased to an undetectable level. They also reported significant inhibition of *Shigella* sp. using the agar diffusion method. The AM activity of carvacrol has also been reported by Ultee and others (2000) when studying the preservation of rice against *B. cereus*. Roller and Seedhar (2002) investigated the effectiveness of carvacrol against the natural flora of freshly cut melons and kiwifruit. They found that carvacrol reduced significantly the viable count of natural flora on kiwifruit dipped in a solution of the agent, but it was less effective on honeydew melons. Kiskó and Roller (2005) explored the AM effectiveness of carvacrol against *E. coli* inoculated into unpasteurised apple juice. They found that carvacrol reduced the bacteria to an undetectable level within the first two days of storage. Ultee and Smid (Ultee and Smid 2001) found carvacrol to be effective against *B. cereus* toxin production in soups to an undetectable level. Chiasson and others (2004) reported effective AM activity of carvacrol and thymol against *E. coli* and *Sal. typhimurium* in minced meat products. Seaberg and others (2003) reported inhibitory effects of carvacrol against *L. monocytogenes* in ready-to-eat beef slices. Recently, Rardniyom (2008) coated carvacrol onto LDPE and nylon films and reported that the AM film inhibited

515 the growth of *E. coli* on Cheddar cheese by log 2.3 and 1.8 CFU g^{-1} on samples stored at 8
516 and 12°C respectively for 15 days.
517 In addition to studies on real foods, several studies have reported the inhibitory effect of
518 carvacrol and thymol both on solid and liquid media as shown in Table 2. On solid media,
519 using the agar diffusion test, López-Malo and others (2005) found that carvacrol and thymol
520 had a significant inhibitory effect against *A. flavus*. Singh and others (2006) investigated the
521 AM activity of thymol against various microorganisms using the agar well diffusion method
522 and showed that thymol inhibited completely the growth of *B. cereus* and *P. aeruginosa*.
523 Tepe and others (2004), reported the positive AM activity of carvacrol and thymol against *B.*
524 *catarrhalis, C. perfringens, B. cereus, Staph. aureus, S. pneumoniae, M. smegmatis* and *P.*
525 *aeruginosa in vitro*. Sivropoulou and others (1996) reported significant AM activity of
526 carvacrol and thymol against *Staph. aureus*. Dorman and Deans (2000) reported effective
527 AM activity of thymol and carvacrol against selected microorganisms including *B. cereus,*
528 *Staph. aureus, L. monocytogenes, E. coli, A. niger* and *S. cerevisiae* using the agar well
529 diffusion method. Olasupo and others (2003b) reported that carvacrol and thymol
530 demonstrated the highest AM activity against *E. coli* and *Sal. typhimurium* using liquid
531 culture compared to other agents including eugenol, nisin, cinnamic acid and diacetyl
532 compounds. Rupika and others (2005) found that carvacrol and/or thymol impregnated into
533 LDPE films had a significant inhibitory activity against *E. coli, Staph. aureus, L. innocua, P.*
534 *aeruginosa, A. niger* and *S. cerevisiae* using the agar disc diffusion assay. Han and others
535 (2005) investigated the effectiveness of carvacrol and thymol coated onto LDPE film against
536 *L. innocua* and *E. coli* in solid and liquid media and observed an inhibitory effect using the
537 agar diffusion method. In the liquid culture test, carvacrol and thymol incorporated into the
538 film reduced significantly the specific growth rate and the final cell concentration of *L.*
539 *innocua*.

Falcone and others (2005) reported that thymol inhibited significantly the growth of *S. cerevisiae* and *B. cereus* in liquid media. They reported that the growth kinetics of *B. cereus* in liquid media is a function of thymol concentration. Ultee and others (1998) investigated the AM activity of carvacrol against *B. cereus* using a liquid culture media and reported that the activity depends on the concentration, exposure time, temperature and pH. Periago and others (2004) studied the AM activity of carvacrol and cymene against the growth of two strains of *L. monocytogenes* and found that carvacrol and cymene reduced microbial growth during the lag and exponential phases. They found that the combination of carvacrol and cymene resulted in a larger decrease in viable counts of *L. monocytogenes* compared with the separate application of these agents. Burt and others (2005) conducted a comparative study of the AM activity of oregano and thyme EO components (carvacrol, thymol, *p*-cymene and γ-terpinene) against the growth of *E. coli* O157:H7 and also found synergistic effects of these components using the checkerboard assay. They reported that carvacrol and thymol demonstrated individual and additive antibacterial activity against *E. coli* O157:H7, but no observable AM activity by *p*-cymene and γ-terpinene was found. Although the vast majority of studies involving essential oils or their extracts suggest a positive and broad spectrum of AM activity, an important aspect that needs more attention is how to minimise the loss of these volatile agents during processing, particularly at high temperatures. Gutiérrez and others (2009) reported AM activity of carvacrol, thymol and cinnamadehyde incorporated into PP against various Gram-negative (*E. coli, Yersinia enterocolitica, P. aeruginosa* and *Sal. choleraesuis*), Gram-positive bacteria (*L. monocytogenes, Staph. aureus, B. cereus* and *Enterococcus faecalis*), yeasts (*Candida Albicans, Debaryomyces hansenii, Zygosaccharomyces rouxii)* and moulds (*Botrytis cinerae, A. flavus, Eurotium, repens, penicllium roqueforti, P. islandicum, P. commune, P. nalgiovensis*). Recently, Persico and

565 others (2009) claimed that carvacrol incorporated into a LDPE film demonstrated an AM
566 activity against *B. thermosphacta*, *L. innocua* and *Carnobacterium. sp* on agar medium.
567
568
569 **2.2.5 Other Natural Antimicrobial Agents**
570 Numerous studies have evaluated the inhibitory effects of other natural AM agents including
571 bacteriocins, plant extracts such as grapefruit seed extract (GFSE), enzymes and spices (see
572 Table 2). Bacteriocins such as nisin are ribosomally synthesised peptides produced by lactic
573 acid bacteria and possess bactericidal properties against a range of microorganisms (Siragusa
574 and others 1999). They were widely studied for their AM activity in packaging films.
575 Grower and others (2004) developed an AM film by coating nisin onto an LDPE film and
576 reported that these coatings were effective against *L. monocytogenes* on solid microbiological
577 media and on the surface of individually packed hotdogs. Natrajan and Sheldon (2000)
578 reported significant AM activity of nisin coated on three different packaging films: polyvinyl
579 chloride (PVC), linear low-density polyethylene (LLDPE) and nylon against *Sal.*
580 *typhimurium* on broiler drumstick skin stored at 4°C. The AM activity of the nisin film was
581 found to be at higher nisin concentrations and when the film was in direct contact with the
582 tested products for a longer period. Kim and others (2002) coated nisin onto LDPE film in
583 order to control naturally-occurring bacteria on packaged fresh oysters and ground beef
584 stored at 3 and 10°C. They claimed that nisin coated onto the film reduced microbial growth
585 at both temperatures in contrast to a non-coated LDPE film. The inhibitory effects of AM-
586 coated films on the growth of coliform bacteria were more evident at 10°C than at 3°C, while
587 the effect on the total aerobic bacteria count was consistently apparent at both temperatures.
588 Siragusa and others (1999) evaluated the AM effectiveness of nisin incorporated into LDPE
589 films against the growth of *B. thermosphacta* inoculated on the surface of a beef carcass.

590 They reported that the films reduced significantly the population of *B. thermosphacta* at the
591 end of a storage period at 4 and 12°C. Scannell and others (2000) investigated the AM
592 activity of nisin immobilised onto polyethylene (PE) and/or nylon films and found that the
593 films reduced the levels of *L. innocua* and *Staph. aureus* in sliced cheese and ham. Mauriello
594 and others (2004) investigated the anti-listerial effect of bacteriocin produced by
595 *Lactobacillus curvatus* 32Y incorporated PE and oriented nylon films. The films were coated
596 with the bacteriocin using three different methods: soaking, spraying and coating and all the
597 films inhibited the growth of *L. monocytogenes* on both solid media and pork steaks.
598 Mauriello and others (2005) coated nisin onto LDPE films in order to control the growth of
599 *Micrococcus luteus* in tryptone soya broth and in raw, pasteurised and UHT milk. The nisin
600 coated onto LDPE films was shown to have an inhibitory effect against the growth of the
601 bacteria in the broth and also reduced microbial counts in the milk products. Cooksey (2001)
602 coated nisin onto LDPE films and evaluated their inhibitory effect against *L. monocytogenes*
603 on packaged hotdogs and reported that coatings containing 2500 IU mL^{-1} or greater of nisin
604 applied to the films effectively inhibited microbial growth on the hotdogs stored under
605 refrigeration for 60 days. Cutter and others (2001) investigated the AM activity of nisin
606 incorporated into PE food packaging films and reported a significant AM effect of the films
607 against *B. thermosphacta*.
608
609 The AM activity of plant extracts was investigated by several researchers and invariably
610 demonstrated an inhibitory effect against various microorganisms. For example, Hong and
611 others (2000) investigated the AM effectiveness of 5% (w/w) propolis extract or clove extract
612 incorporated into LDPE films against *E. coli*, *L. plantarum*, *S. cerevisiae* and *Fusarium*
613 *oxysporum*. All extracts demonstrated an inhibitory activity on the growth of *L. plantarum*
614 and *F. oxysporum*. Ha and others (2001) investigated the AM activity of GFSE incorporated

615 into multi-layered PE films against *M. flavus, E. coli, Staph. aureus* and *B. subtilis* on ground
616 beef. The coated films demonstrated an AM activity against all the microorganisms studied.
617 Lee and others (1998) developed an LDPE packaging film incorporated with GFSE and
618 reported that the film containing narigin, ascorbic acid, hesperidin and various organic acids
619 was shown to possess a wide spectrum of AM activity. However, although the LDPE films
620 containing GFSE had an inhibitory effect on the growth of *E. coli* and *Staph. aureus* on solid
621 media, they were unable to inhibit the growth of *Leuconostoc mesenteroides, S. cerevisiae,*
622 *Aspergillus oryzaei*, *A. niger* and *Penicillium chrysogenum.* Rodriguez and others (2008)
623 investigated the AM activity of an active packaging film incorporated with cinnamon EOs
624 against *Rhizopus stolonifer* both *in vitro* and on sliced bread. They reported that cinnamon
625 EOs inhibited the growth of *R. stolonifer* on solid media and on sliced bread.
626
627 The AM films incorporated with EOs and/or their principal constituents have the potential for
628 packaging of many food products such as bakery (Suhr and Nielsen 2003; Rodríguez and
629 others 2008; Rokchoy and others 2009; Mehyar and others 2011), dairy (Suppakul and others
630 2008; Kuorwel and others 2011a), meat, chicken and fish (Suppakul and others 2003a; Kerry
631 and others 2006; Wu and others 2010), and fresh produce (Rodríguez-Lafuente and others
632 2010). There are already some commercial applications for AM packaging systems such as
633 wasabi extract (or Japanese horseradish) used for Japanese rice lunch boxes (Koichiro 1993),
634 Piatech manufactured by Rhone-Poulene (USA) and Daikoku Kasei Co (Japan) (Brody and
635 others 2001).
636

637 ## 3 Conclusions

638 In recent years, an increasing interest has emerged in the development of various forms of
639 active packaging systems intended to protect food products from microbial contamination.

Many synthetic and natural AM agents incorporated into or coated onto synthetic polymer-based packaging materials have demonstrated significant AM activity against various microorganisms. Although incorporating synthetic AM agents directly into foods can effectively inhibit the growth and survival of various microorganisms, consumers today demand minimally processed, preservative-free food products with a longer shelf life. Thus, natural AM agents such as basil, thyme and oregano EOs with their main components linalool, thymol and carvacrol respectively are well suited to be utilised as preservatives in foods and as potential alternatives for synthetic food additives. Packaging materials containing AM agents demonstrate a potential for applications in AM packaging systems that could reduce the risk of food-borne illness associated with microbial contamination in food products. Although the commercial applications of these systems is not yet widespread, it is anticipated that AM packages containing natural AM agents would be one of the new developments in food packaging (cheeses, processed meats, fish, bakery, fruits and vegetables and more) in the near future.

654 **Table 1: Antimicrobial activity of common synthetic AM agents**

655

AM Agent	Amount added	Packaging Material	Test Type/Media	Target Microorganism(s)	Findings	References
Benzoic acid	0.5 mol/L	PEMA	PDA	*A. niger* and *Penicillium* sp.	Inhibited microbial growth	Weng and others (1999)
Benzoic acid	0.5-2% w/w	LDPE	Agar media; Cheddar cheese	*R. stolonifer*, *Penicillium* sp. and *A. toxacarius*	Failed to inhibit mould growth	Weng and Hotchkiss (1993)
Benzoic anhydride	0.5-2% w/w	LDPE	Agar media; Cheddar cheese	*R. stolonifer*, *Penicillium* sp. and *A. toxacarius*	Demonstrated antimycotic activity on media and cheese	Weng and Hotchkiss (1993)
EDTA	5% w/w	LDPE	Agar diffusion	*B. subtilis*, *A. niger* and *E. coli*	Inhibited *B. subtilise* and *A. Niger* but not *E. coli*	Vartiainen and others (2003a)
Imazalil	1000-2000 mg/kg	LDPE	Agar media; Cheddar	*A. toxacarius*, *Penicillium* sp.	All concentrations delayed microbial growth on media	Weng and Hotchkiss (1992)

AM Agent	Amount added	Packaging Material	Test Type/Media	Target Microorganism(s)	Findings	References
			cheese		and cheese	
Imazalil	0.05-0.25% w/w	LDPE	Agar diffusion	*B. subtilis*, *A. niger* and *E. coli*	Inhibited *B. subtilise* and *A. Niger* but not *E. coli*	Vartiainen and others (2003a)
Potassium sorbate	2-3% w/v	PVC	Agar media	*L. monocytogenes*	Films inhibited microbial growth	Limjaroen and others (2003)
Propionic acid	0.5-2% w/w	LDPE	Agar media; Cheddar cheese	*R. stolonifer*, *Penicillium* sp. and *A. toxacarius*	Failed to inhibit mould growth	Weng and Hotchkiss (1993)
Propionic anhydride	0.5-2% w/w	LDPE	Agar media; Cheddar cheese	*R. stolonifer*, *Penicillium* sp. and *A. toxacarius*	Failed to inhibit mould	Weng and Hotchkiss (1993)
Sodium propionate	0.5-2% w/w	LDPE	Agar media; Cheddar cheese	*R. stolonifer*, *Penicillium* sp. and *A. toxacarius*	Failed to inhibit mould	Weng and Hotchkiss (1993)

AM Agent	**Amount added**	**Packaging Material**	**Test Type/Media**	**Target Microorganism(s)**	**Findings**	**References**
Sodium diacetate	0.5-3% w/v	PVC	Agar media	*L. monocytogenes*	No AM activity observed	Limjaroen and others (2003)
Sorbic acid	1.5-3% w/v	PVC	Agar media	*L. monocytogenes*	Inhibited microbial growth	Limjaroen and others (2003)
Sorbic acid	0.5-2% w/w	LDPE	Agar media; Cheddar cheese	*R. stolonifer*, *Penicillium* sp. and *A. toxacarius*	Failed to inhibit mould	Weng and Hotchkiss (1993)
Sorbic acid	0.5 mol L^{-1}	PEMA	PDA	*A. niger* and *Penicillium* sp.	Inhibited microbial growth	Weng and others (1999)
Triclosan	500-1000 mg kg^{-1}	LDPE	Agar diffusion; Chicken breasts	*L. monocytogenes, Sal. enteritidis, Staph. aureus, E. coli* O157:H7, *B. thermosphacta, B. cereus, L. sake, L. brevis, P.*	Inhibited *L. monocytogenes, Sal. enteritidis, Staph. aureus, E. coli* O157:H7 with slight inhibition of *B.*	Vermeiren and others (2002)

AM Agent	Amount added	Packaging Material	Test Type/Media	Target Microorganism(s)	Findings	References
				Roqueforti, A. niger and *C. albicans*	*thermosphacta,* but no activity against, *B. cereus, L. sake, L. brevis, P. Roqueforti, A. niger* and *C. Albicans*	
Triclosan	5% w/w	PVC	Plate count	*Staph. aureus, E. coli*	*Staph. aureus, E. coli*	Ji and Zhang (2009)

656

657 **Table 2: Antimicrobial activity of natural AM agents**

658

Antimicrobial Agent	**Amount added**	**Packaging Material**	**Test Type/Media**	**Target Microorganism(s)**	**Findings**	**References**
Carvacrol	1.33-2.65% w/w	LDPE	Liquid culture	*E. coli*	Reduced microbial growth	Rupika and others (2008)
Carvacrol	1-4% w/w	PP	Agar medium	*E. coli, Y. enterocolitica, P. aeruginosa, Staph. aureus, B. cereus* and *E. faecalis, C. albicans, D. hansenii, Z. Rouxii, A. flavus, E. repens, p. roqueforti, P. commune*	Carvacrol demonstrated AM activity against all the tested microorganisms	Gutiérrez and others (2009)
Carvacrol	1-4% w/w 1-21.8µL/L	PP, PE/EVOH	Agar medium or vapour diffusion	*L. monocytogenes, Sal. choleraesuis, A. flavus* and *C. albicans*	carvacrol inhibited the growth of all the tested microorganisms	Lopez and others (2007b; 2007a)

Antimicrobial Agent	**Amount added**	**Packaging Material**	**Test Type/Media**	**Target Microorganism(s)**	**Findings**	**References**
			method			
Carvacrol	0.2-2% w/w	LDPE	Agar media	*E. coli, Staph. aureus, L. innocua, P. aeruginosa, A. niger* and *S. cerevisiae*	Inhibited *E. coli, Staph. aureus, A. niger* and *S. cerevisiae* but not *L. innocua* or *P. aeruginosa*	Rupika and others (2005)
Carvacrol	10% w/w	LDPE	Agar media	*B. thermosphacta, L. innocua* and *Carnobacterium. sp*	Carvacrol demonstrates *B. thermosphacta, L. innocua* and *Carnobacterium. sp*	Persico and others (2009)
Carvacrol	4% w/w	LDPE and nylon film	liquid food media; Cheddar cheese	*E. coli*	Multilayer films inhibited microbial growth	Rardniyom and others (2008)

Antimicrobial Agent	**Amount added**	**Packaging Material**	**Test Type/Media**	**Target Microorganism(s)**	**Findings**	**References**
Cinnamaldehyde	1-4% w/w	PP	Agar medium	*E. coli, Y. enterocolitica, P. aeruginosa, Staph. aureus, B. cereus* and *E. faecalis, C. albicans, D. hansenii, Z. Rouxii, A. flavus, E. repens, p. roqueforti, P. commune*	cinnamaldehyde demonstrated AM activity against all the tested microorganisms	Gutiérrez and others (2009)
Cinnamaldehyde	1-4% w/w 0.4-21.8µL/L	PP, PE/EVOH	Agar medium or vapour diffusion method	*L. monocytogenes, Sal. choleraesuis, A. flavus* and *C. albicans*	Cinnamaldehyde inhibited the growth of all the tested microorganisms	Lopez and others (2007b; 2007a)
Clove extract	20% w/w	LDPE	Liquid culture	*E. coli*, *L. plantarum*, *S. cerevisiae* and *F. oxysporum*	Effective against *L. plantarum* and *F. oxysporum* but not against	Hong and others (2000)

Antimicrobial Agent	**Amount added**	**Packaging Material**	**Test Type/Media**	**Target Microorganism(s)**	**Findings**	**References**
					E. coli and *S. cerevisiae*	
GFSE	0.1 or 1% w/w	LDPE	Agar media; Curled lettuce; Soybean sprouts	*E. coli*, *Staph. aureus, L. mesenteroides, S. cerevisiae, A. oryzaei, A. niger, P. chrysogenum*	Inhibited *E. coli* and *Staph. aureus* but not *S. cerevisiae, A. oryzaei, A. niger,* or *P. chrysogenum*.	Lee and others (1998)
GFSE	0.5% or 1% w/v	Multi-layered PE (coated)	Ground beef, Agar media	*M. flavus*, *P. aeruginosa, E. coli, Staph. aureus* and *B. subtilise, S. cerevisiae, A. Niger, P. chysogenum, L. mesenteroides*	AM activity against *M. flavus*, *E. coli, Staph. aureus* and *B. subtilise*	Ha and others (2001)
Lactoferrin	0.5-2.5% w/v	PVC	Agar media	*L. monocytogenes*	No AM activity	Limjaroen and others (2003)
Lacticin NK24	20 gL^{-1}	LDPE	Fresh oysters;	Coliform, total aerobic	Inhibited microbial growth	Kim and others (2002)

Antimicrobial Agent	**Amount added**	**Packaging Material**	**Test Type/Media**	**Target Microorganism(s)**	**Findings**	**References**
			ground beef	bacteria		
Linalool	0.037% w/w	LDPE	Agar media	*E. coli*	Linalool incorporated into LDPE film inhibit the growth of *E. Coli* after 1 year of storage	Suppakul and others (2011b)
Linalool	0.338% w/w	LDPE	Agar media; Cheddar cheese	*E. coli, L. innocua, S. cerevisiae*	Inhibitory activity against *E. Coli* but not *L. innocua* or *S. cerevisiae* on agar media; reduced *E. coli* and *L. innocua* on cheese	Suppakul (2004; 2006; 2008)
Linalool	4% w/w	LDPE and nylon film	Liquid culture; Cheddar cheese	*E. coli*	Multilayer films inhibited microbial growth	Rardniyom and others (2008)

Antimicrobial Agent	**Amount added**	**Packaging Material**	**Test Type/Media**	**Target Microorganism(s)**	**Findings**	**References**
Linalool	0.54-1.19% w/w	LDPE	Agar and liquid media; Cheddar cheese	*E. coli, L. innocua*	Inhibited microbial growth	Rupika and others (2006)
Methylchavicol	0.028% w/w	LDPE	Agar media	*E. coli*	Methylchavicol inhibitory activity against the growth of *E. Coli* after 1 year of storage	Suppakul and others (2011b)
Methylchavicol	0.345% w/w	LDPE	Agar media; Cheddar cheese	*E. coli, L. innocua, S. cerevisiae*	Inhibitory activity against *E. coli* but not against *L. innocua* or *S. cerevisiae* on agar media	Suppakul (2004; 2006; 2008)
Nisin	0.05 or	LDPE	Beef carcass	*B. thermosphacta*	Inhibited microbial growth	Siragusa and others

Antimicrobial Agent	**Amount added**	**Packaging Material**	**Test Type/Media**	**Target Microorganism(s)**	**Findings**	**References**
	0.1% w/v					(1999)
Nisin	2-2.5% w/v	PVC	Agar media	*L. monocytogenes*	Inhibited microbial growth	Limjaroen and others (2003)
Nisin	157 mg/mL	LDPE	Agar media	*L. monocytogenes*	Inhibited microbial growth	Grower and others (2004)
Nisin	100 µg/mL	LLDPE, PVC, nylon	Broiler skin	*Sal. typhimurium*	Significantly reduced microbial population	Natrajan and Sheldon (2000)
Nisin	20 g/L	LDPE	Fresh oysters; ground beef	coliform, total aerobic bacteria	Suppressed coliform and bacterial growth	Kim and others (2002)
Nisin	0.03 or 0.6 g/mL	PE or polyamide	Sliced cheese; ham	*L. innocua* and *Staph. aureus*	Reduced microbial growth in cheese	Scannell and others (2000)
Propolis	20% w/w	LDPE	Liquid culture	*E. coli*, *L. plantarum*, *S. cerevisiae* and *F. oxysporum*	Inhibited *L. plantarum* and *F. oxysporum* but not *E. coli* or *S. cerevisiae*	Hong and others (2000)

Antimicrobial Agent	**Amount added**	**Packaging Material**	**Test Type/Media**	**Target Microorganism(s)**	**Findings**	**References**
Thymol	0.85-3.15% w/w	LDPE	Liquid culture	*E. coli*	Inhibited microbial growth	Rupika and others (2008)
Thymol	1-4% w/w	PP	Agar medium	*E. coli, Y. enterocolitica, P. aeruginosa, Staph. aureus, B. cereus* and *E. faecalis, C. albicans, D. hansenii, Z. Rouxii, A. flavus, E. repens, p. roqueforti, P. commune*	Thymol demonstrated AM activity against all the tested microorganisms	(Gutiérrez and others 2009)
Thymol	0.23-1.6% w/w	LDPE	Agar media	*E. coli, Staph. aureus, L. innocua, P. aeruginosa, A. niger* and *S. cerevisiae*	Inhibited *E. coli, Staph. aureus, A. niger* and *S. cerevisiae* but not *L. innocua,* and *P. aeruginosa*	Rupika and others (2005)

Antimicrobial Agent	**Amount added**	**Packaging Material**	**Test Type/Media**	**Target Microorganism(s)**	**Findings**	**References**
Thymol	1-4% w/w 1-21.8µL/L	PP, PE/EVOH	Agar medium or vapour diffusion method	*L. monocytogenes, Sal. choleraesuis, A. flavus* and *C. albicans*	Thymol inhibited the growth of all the tested microorganisms	Lopez and others (2007b; 2007a)
Basil EOs				*E. coli, Staph. aureus, seven strains of Candida*	Inhibited microbial growth	Mazzanti and others (1998)
Basil EOs			Solid media	25 strains of bacteria	Inhibited microbial growth	Dorman and Deans (2000)
Basil EOs			Solid media	*Staph. aureus*	Inhibited microbial growth	Baratta and others (1998)
Basil EOs			Solid media Food	*Bacillus* sp., *Staph. aureus* sp., *micrococcus* sp., *Sarcina* sp., *Lactobacillus* sp., *E. coli, Salmonella,*	Inhibitory effects against Gram-positives (*Bacillus* sp., *Staph. aureus* sp., *micrococcus* sp., *Sarcina*	Lachowicz and others (1998)

Antimicrobial Agent	**Amount added**	**Packaging Material**	**Test Type/Media**	**Target Microorganism(s)**	**Findings**	**References**
				sp., *Enterobacter* sp., *Pseudomonas* sp.	sp. and *Lactobacillus* sp. Reduced effects against Gram-negatives (*E. coli, Salmonella* sp., *Enterobacter* sp. and *Pseudomonas* sp.	
Basil EOs				*Fusarium acuminatum, F. solani, F. pallidoroseum* and *F. chlamydosporum*	EOs effective against all *Fusarium* species	Rai and others (1999)
Cinnamon EOs	1-4% w/w 13.1-131µL/L	PP, PE/EVOH	Agar medium or vapour diffusion method	*E. coli, Y. enterocolitica, P. aeruginosa, Staph. aureus, B. cereus* and *E. faecalis, C. albicans, D. hansenii, Z. Rouxii, A.*	Cinnamon EOs in PP or PE/EVOH demonstrated AM activity against all the tested microorganisms	Lopez and others (2007b; 2007a)

Antimicrobial Agent	**Amount added**	**Packaging Material**	**Test Type/Media**	**Target Microorganism(s)**	**Findings**	**References**
				flavus, E. repens, p. roqueforti, P. commune		
Cinnamon EOs	3-6% (w/w)	Paraffin-based paper	*In vitro,* Sliced bread	*A. alternata*	Cinnamon EOs inhibited the growth of *A. alternata* on solid media	Rodriquez-Lafuente and others (2010)
Cinnamon EOs	1-6% w/w	Paraffin-paper	*In vitro,* Sliced bread	*R. stolonifer*	Cinnamon EOs in paraffin film inhibited the growth of *R. stolonifer*	Rodríguez and others (2008)
Clove	1-4% w/w	PP, PE/EVOH	Agar medium	*E. coli, Y. enterocolitica, P. aeruginosa, Staph. aureus, B. cereus* and *E. faecalis, C. albicans, D. hansenii, Z. Rouxii, A. flavus, E. repens, p.*	Clove EOs demonstrated AM activity against all the tested microorganisms	Lopez and others (2007b; 2007a)

Antimicrobial Agent	**Amount added**	**Packaging Material**	**Test Type/Media**	**Target Microorganism(s)**	**Findings**	**References**
				roqueforti, P. commune		
Oregano EOs	0.8% (v/w)	surface dipping, O_2 permeable films	beef meat fillets	*L. monocytogenes,* autochthonous flora	Reduced growth by 2-3 log_{10}	Tsigarida and others (2000)
Oregano EOs	3-6% (w/w)	Paraffin-based paper	*In vitro,* Cherry tomato	*A. alternata*	Oregano EOs inhibited the growth of *A. alternata* on solid media	Rodriquez-Lafuente and others (2010)
Oregano EOs		dressing, MAP	fresh fish fillets	*Staph. aureus, Sal. enteritidis,* Residential flora	Bacterostatic and bactericidal effects	Tassou and others (1996)
Oregano EOs	800 ppm	surface spreading	thin-sliced beef	*L. monocytogenes*	Significant inhibition	Seaberg and others (2003)
Oregano EOs	0.05-1%	PE bags	minced beef	spoilage microbiota	Reduction in microbial	Skandamis and

Antimicrobial Agent	**Amount added**	**Packaging Material**	**Test Type/Media**	**Target Microorganism(s)**	**Findings**	**References**
	(v/w)				loads	Nychas (2001)
Oregano EOs		surface application	raw fish fillets	*Photobacterium phosphoreum*	No significant growth reduction	Mejlholm and Dalgaard (2002)
Oregano EOs	1-4% w/w 13.1-175µL/L	PP, PE/EVOH	Agar medium or Vapour diffusion method	*E. coli, Y. enterocolitica, P. aeruginosa, Staph. aureus, B. cereus* and *E. faecalis, C. albicans, D. hansenii, Z. Rouxii, A. flavus, E. repens, p. roqueforti, P. commune*	Oregano EOs in PP or PE/EVOH demonstrated AM activity against all the tested microorganisms	Lopez and others (2007b; 2007a)
Oregano EOs	50 µL	Suspensions of oils in apple juice	Apple juices	*E. coli, Sal. enterica*	Selected oils were bactericidal	Friedman and others (2004)
Oregano EOs	0.1-10%	dissolved in	Liquid	*Sal. enterica*	OEO showed strongest	Marques and others

Antimicrobial Agent	**Amount added**	**Packaging Material**	**Test Type/Media**	**Target Microorganism(s)**	**Findings**	**References**
	(v/v)	brain heart infusion broth	culture		AM activity	(2008)
Oregano EOs			*In vitro*	*B. cereus, E. coli L. monocytogenes*	Inhibited microbial growth	Baydar and others (2004)
Thyme EOs	50 μL	vapour contact	sponge cake analogues	*Eurotium* sp., *Aspergillus* sp., *Pencillium* sp.	Significant reduction in microbial growth	Guynot and others (2003)
Thyme EOs	135 or 270 μL/L	vapour contact	rye bread	*Pencillium* sp., *E. repens, A. flavus*	Significant reduction in microbial growth	Suhr and Nielsen (2003)
Thyme EOs	0.1-1% (v/v)	cheese-EO-mixture	soft cheese	*L. monocytogenes* *Sal. enteritidis*	Significant inhibition in low-fat cheese; no inhibition in full-fat cheese	Smith-Palmer and others (2001)
Thyme EOs	1:5 dilution	surface application	cooked poultry	*A. hydrophila, L. monocytogenes*	Inhibited growth of *A. Hydrophila*	Hao and others (1998)

Antimicrobial Agent	**Amount added**	**Packaging Material**	**Test Type/Media**	**Target Microorganism(s)**	**Findings**	**References**
Thyme EOs	1-4% w/w 26.2-175µL/L	PP, PE/EVOH	Agar medium, Vapour diffusion method	*E. coli, Y. enterocolitica, P. aeruginosa, Staph. aureus, B. cereus* and *E. faecalis, C. albicans, D. hansenii, Z. Rouxii, A. flavus, E. repens, p. roqueforti, P. commune*	thyme EOs demonstrated AM activity against all the tested microorganisms	Lopez and others (2007b; 2007a)
Thyme EOs		surface application	raw fish fillets	*Photobacterium phosphoreum*	No significant growth reduction	Mejlholm and Dalgaard (2002)

659

List of Abbreviations and Nomenclature

AM	Antimicrobial
AP	Active Packaging
CFU	Colony Forming Units
EOs	Essential Oils
EVOH	Ethylene Vinyl Alcohol
GRAS	Generally Recognized As Safe
GFSE	Grapefruit Seed Extract
HDPE	High-Density Polyethylene
LB	Lactic-acid Bacteria
LDPE	Low-Density Polyethylene
LLDPE	Linear Low-Density Polyethylene
MAP	Modified Atmosphere Packaging
OEO	Oregano Essential Oil
PDA	Potato Dextrose Agar
PE	Polyethylene
PEG	Polyethylene Glycol
PEMA	Poly(Ethylene-*co*-Methacrylic Acid)
PET	Polyethylene Terephthalate
PP	Polypropylene
PS	Polystyrene
PVC	Polyvinyl Chloride
PVDC	Poly(Vinylidene Chloride) or Poly(Vinyl Dichloride)
TEO	Thyme Essential Oil

4 References

An DS, Hwang YI, Cho SH, Lee DS. 1998. Packaging of fresh curled lettuce and cucumber by using low density polyethylene films impregnated with antimicrobial agents. J Korean Soc Food Sci Nutr 27 (4):675-81.

Appendini P, Hotchkiss JH. 1997. Immobilization of lysozyme on food contact polymers as potential antimicrobial films. Packag Technol Sci 10 (5):271-9.

Appendini P, Hotchkiss JH. 2002. Review of antimicrobial food packaging. Innov Food Sci Emerg Technol 3 (2):113-26.

Azaz AD, Kurkcuoglu M, Satil F, Baser HC, Tumen G. 2005. In vitro antimicrobial activity and chemical composition of some Satureja essential oils. Flavour Frag J 20 (6):587-91.

Bagamboula CF, Uyttendaele M, Debevere J. 2004. Inhibitory effect of thyme and basil essential oils, carvacrol, thymol, estragol, linalool and *p*-cymene towards *Shigella sonnei* and *S. flexneri*. Food Microbiol 21 (1):33-42.

Bakkali F, Averbeck S, Averbeck D, Idaomar M. 2008. Biological effects of essential oils - a review. Food Chem Toxicol 46 (2):446-75.

Baratta TM, Dorman TJH, Denes GS, Figueiredo CA, Barroso GJ, Ruberto G. 1998. Antimicrobials and antioxidant properties of some commercial oils. Flavour Frag J 13 (4):235-44.

Basílico MZ, Basílico JC. 1999. Inhibitory effects of some spice essential oils on *Aspergillus ochraceus* NRRL 3174 growth and ochratoxin A production. Lett Appl Microbiol 29 (4):238-41.

Baydar H, Sagdiç O, Özkan G, Karadogan T. 2004. Antibacterial activity and composition of essential oils from *Origanum*, *Thymbra* and *Satureja* species with commercial importance in Turkey. Food Control 15 (3):169-72.

Becerril R, Gómez-Lus R, Goñi P, López P, Nerín C. 2007. Combination of analytical and microbiological techniques to study the antimicrobial activity of a new active food packaging containing cinnamon or oregano against *E. coli* and *S. aureus*. Anal Bioanal Chem 388 (5):1003-11.

Bezic N, Skocibusic M, Dunkic V, Radonic A. 2003. Composition and antimicrobial activity of *Achillea clavennae L.* essential oil. Phytother Res 17 (9):1037-40.

Brody AL, Strupinsky ER, Kline LR. 2001. Antimicrobial packaging. In: Active packaging for food applications. Lancaster, Penn.: Technomic Publishing Co. p. 131-96.

Burt S. 2004. Essential oils: Their antibacterial properties and potential applications in foods-a review. Int J Food Microbiol 94 (3):223-53.

Burt S, Vlielander R, Haagsman H, Veldhuizen E. 2005. Increase in activity of essential oil components carvacrol and thymol against *Escherichia coli* O157:H7 by addition of food stabilisers. J Food Protect 68 (5):919-26.

Camilloto GP, Ana Clarissa SP, Nilda de Fátima FS, Emiliane AA, Nélio JA, Sukarno OF. 2010. Effect of active packaging incorporated with triclosan on bacteria adhesion. J Food Sci 75 (8):E557-E64.

Cha DS, Chinnan MS. 2004. Biopolymer-based antimicrobial packaging: A review. Crit Rev Food Sci Nutr 44 (4):223-37.

Chen MC, Yeh GHC, Chiang BH. 1996. Antimicrobial and physicochemical properties of methylcellulose and chitosan films containing a preservative. J Food Process Pres 20 (5):379-90.

Chiasson F, Borsa J, Ouattara B, Lacroix M. 2004. Radiosensitisation of *Escherichia coli* and *Salmonella typhi* in ground beef. J Food Protect 67 (6):1157-62.

Chung D, Spyridon EP, Yam KL. 2003a. Evaluation of a polymer coating containing triclosan as the antimicrobial layer for packaging materials. Int J Food Sci Technol 38 (2):165-9.
Chung Y-C, Wang H-L, Chen Y-M, Li S-L. 2003b. Effect of abiotic factors on the antibacterial activity of chitosan against waterborne pathogens. Bioresource Technol 88 (3):179-84.
Coma V. 2007. Bioactive packaging technologies for extended shelf life of meat-based products. Meat Sci 78 (1-2):90-103.
Conner DE, Beuchat LR. 1984. Effects of essential oils from plants on growth of food spoilage yeasts. J Food Sci 49 (2):429-34.
Cooksey K. 2000. Utilisation of antimicrobial packaging films for inhibition of selected microorganisms. In: Risch SJ, editor. Food Packaging. Washington: American Chemical Society. p. 17-25.
Cooksey K. 2001. Antimicrobial food packaging materials. Addit Polym 2001 (8):6-10.
Cooksey K. 2005. Effectiveness of antimicrobial food packaging materials. Food Addit Contam 22 (10):980-7.
Cosentino S, Tuberoso CIG, Pisano B, Satta M, Mascia V, Arzedi E, Palmas F. 1999. *In-vitro* antimicrobial activity and chemical composition of Sardinian *Thymus* essential oils. Lett Appl Microbiol 29 (2):130-5.
Couladis M, Tzakou O, Kujundzic S, Sokovic M, Mimica-Dukic N. 2004. Chemical analysis and antifungal activity of *Thymus striatus*. Phytother Res 18 (1):40-2.
Cran MJ, Rupika LAS, Sonneveld K, Miltz J, Bigger SW. 2010. Release of naturally derived antimicrobial agents from LDPE films. J Food Sci 75 (2):E126-E33.
Cutter CN. 1999. The effectiveness of triclosan-incorporated plastic against bacteria on beef surfaces. J Food Protect 62 (5):474-9.
Cutter CN, Willett JL, Siragusa GR. 2001. Improved antimicrobial activity of nisin-incorporated polymer films by formulation change and addition of food grade chelator. Lett Appl Microbiol 33 (4):325-8.
Davidson PM, Naidu AS. 2000. Phyto-phenols In: Naidu AS, editor. Natural Food Antimicrobial Systems. Boca Raton, Flor.: CRC Press. p. 265-94.
Davidson PM, Zivanovic S. 2003. The use of natural antimicrobials. In: Zeuthen P, Bogh-Sorensen L, editors. Food Preservation Techniques. Boca Raton, Flor.: Woodhead Publishing Limited and CRC Press LLC. p. 5-30.
Davidson PM, Sofos JN, Branen AL. 2005. Antimicrobials in foods. Boca Raton, Flor.: CRC press, Taylor & Francis Group. 706 p.
Davidson PM, Taylor MT. 2007. Chemical preservatives and natural antimicrobial compounds. In: Doyle P, Beuchat LR, Montville TJ, editors. Food Microbiology: Fundamentals and Frontiers. Washington: American Society for Microbiology Press. p. 713-34.
de Oliveira TM, de Fátima Ferreira Soares N, Magela Pereira R, de Freitas Fraga K. 2007. Development and evaluation of antimicrobial natamycin-incorporated film in gorgonzola cheese conservation. Packag Technol Sci 20 (2):147-53.
Deans JG, Ritchie G. 1987. Antimicrobial properties of plant essential oils. Int J Food Microbiol 5 (2):165-80.
Devlieghere F, Vermeiren L, Bockstal A, Debevere J. 2000a. Study on antimicrobial activity of a food packaging materials containing potassium sorbate. Acta Aliment 29 (2):137-46.

781 Devlieghere F, Vermeiren L, Jacobs M, Debevere J. 2000b. The effectiveness of
782 hexamethylenetetramine-incorporated plastic for the active packaging of
783 foods. Packag Technol Sci 13 (3):117-22.
784 Devlieghere F, Vermeiren L, Debevere J. 2004a. New preservation technologies:
785 Possibilities and limitations. Int Dairy J 14 (4):273-85.
786 Devlieghere F, Vermeulen A, Debevere J. 2004b. Chitosan: Antimicrobial activity,
787 interactions with food components and applicability as a coating on fruit and
788 vegetables. Food Microbiol 21 (6):703-14.
789 Dorman HJD, Deans SG. 2000. Antimicrobial agents from plants: Antibacterial
790 activity of plant volatile oils. J Appl Microbiol 88 (2):308-16.
791 Du W-X, Olsen CW, Avena-Bustillos RJ, McHugh TH, Levin CE, Friedman M. 2008.
792 Storage stability and antibacterial activity against *Escherichia coli* O157:H7 of
793 carvacrol in edible apple films made by two different casting methods. J Agric
794 Food Chem 56 (9):3082-8.
795 Elgayyar M, Draughon FA, Golden DA, Mount JR. 2001. Antimicrobial activity of
796 essential oils from plants against selected pathogenic and saprophytic
797 microorganisms. J Food Protect 67 (7):1019-24.
798 Falcone P, Speranza B, Del Nobile MA, Corbo MR, Sinigaglia M. 2005. A study on
799 the antimicrobial activity of thymol intended as a natural preservative. J Food
800 Protect 68 (8):1664-70.
801 Farag RS, Daw ZY, Abo-Raya SH. 1989. Influence of some spice essential oils on
802 *Aspergillus parasiticus* growth and production of aflatoxins in a synthetic
803 medium. J Food Sci 54 (1):74-6.
804 Farkas J. 2007. Physical methods of food preservation. In: Doyle P, Beuchat LR,
805 Montville TJ, editors. Food Microbiology: Fundamentals and Frontiers.
806 Washington: American Society for Microbiology Press. p. 685-705.
807 Fisher K, Phillips C, McWatt L. 2009. The use of an antimicrobial citrus vapour to
808 reduce *Enterococcus* sp. On salad products. Int J Food Sci Technol 44
809 (9):1748-54.
810 Fitzgerald DJ, Stratford M, Narbad A. 2003. Analysis of the inhibition of food
811 spoilage yeasts by vanillin. Int J Food Microbiol 86 (1-2):113-22.
812 Friedman M, Henika PR, Mandrell RE. 2002. Bactericidal activities of plant essential
813 oils and some of their isolated constituents against *Campylobacter jejuni*,
814 *Escherichia coli*, *Listeria monocytogenes*, and *Salmonella enterica*. J Food
815 Protect 65 (10):1545-60.
816 Friedman M, Henika PR, Levin CE, Mandrell RE. 2004. Antibacterial activities of
817 plant essential oils and their components against *Escherichia coli* O157:H7
818 and *Salmonella enterica* in apple juice. J Agric Food Chem 52 (19):6042-8.
819 Fyfe L, Armstrong F, Stewart J. 1998. Inhibition of *Listeria monocytogenes* and
820 *Salmonella enteritidis* by combinations of plant oils and derivatives of benzoic
821 acid: The development of synergistic antimicrobial combinations. Int J
822 Antimicrob Ag 9 (3):130-6.
823 Goñi P, López P, Sánchez C, Gómez-Lus R, Becerril R, Nerín C. 2009. Antimicrobial
824 activity in the vapour phase of a combination of cinnamon and clove essential
825 oils. Food Chem 116 (4):982-9.
826 Grower JL, Cooksey K, Getty KJK. 2004. Development and characterization of an
827 antimicrobial packaging film coating containing nisin for inhibition of *Listeria*
828 *monocytogenes*. J Food Protect 67 (3):475-9.

Gustafson JE, Liew YC, Chew S, Markham JL, Bell HC, Wyllie SG, Warmington JR. 1998. Effects of tea tree oil on *Escherichia coli*. Lett Appl Microbiol 26 (3):194-8.
Gutierrez J, Barry-Ryan C, Bourke P. 2008. The antimicrobial efficacy of plant essential oil combinations and interactions with food ingredients. Int J Food Microbiol 124 (1):91-7.
Gutierrez J, Barry-Ryan C, Bourke P. 2009. Antimicrobial activity of plant essential oils using food model media: Efficacy, synergistic potential and interactions with food components. Food Microbiol 26 (2):142-50.
Gutiérrez L, Escudero A, Batlle Rn, Nerín C. 2009. Effect of mixed antimicrobial agents and flavors in active packaging films. J Agric Food Chem 57 (18):8564-71.
Guynot ME, Ramos AJ, Setó L, Purroy P, Sanchis V, Marín S. 2003. Antifungal activity of volatile compounds generated by essential oils against fungi commonly causing deterioration of bakery products. J Appl Microbiol 94 (5):893-9.
Ha JU, Kim YM, Lee DS. 2001. Multilayered antimicrobial polyethylene films applied to the packaging of ground beef. Packag Technol Sci 15 (2):55-62.
Halek WG, Anita G. 1989. Fungal inhibition by a fungicide coupled to an ionomeric film. J Food Safety 9 (3):215-22.
Han J, Castell-Perez ME, Moreira RG. 2005. Antimicrobial films as a potential technology to increase pathogen radiation sensitivity. Proceedings of IFT Annual Meeting. New Orleans, Lou., July 15-20.
Han JH, Floros JD. 1997. Casting antimicrobial packaging films and measuring their physical properties and antimicrobial activity. J Plastic Film Sheeting 13 (4):287-98.
Han JH, Floros JD. 1998. Simulating diffusion model and determining diffusivity of potassium sorbate through plastics to develop antimicrobial packaging film. J Food Process Pres 22 (2):107-22.
Han JH. 2000. Antimicrobial food packaging. Food Technol 54 (3):56-65.
Han JH. 2003. Antimicrobial food packaging. In: Ahvenainen R, editor. Novel Food Packaging Techniques. Cambridge: Woodhead Publishing Limited. p. 50-70.
Han JH. 2005. Antimicrobial packaging systems. In: Han JH, editor. Innovations in Food Packaging. San Diego, Calif.: Elsevier Academic Press. p. 92-108.
Helander IM, Alakomi HL, Latva KK, Mattila ST, Pol I, Smid EJ, Wright VA. 1998. Characterisation of the action of selected essential oil components on gram-negative bacteria. J Agric Food Chem 46 (9):3590-5.
Hoffman KL, Han IY, Dawson PL. 2001. Antimicrobial effects of corn zein films inpregnated with nisin, lauric acid and EDTA. J Food Protect 64 (6):885-9.
Hong S-I, Park J-D, Him D-M. 2000. Antimicrobial and physical properties of food packaging films incorporated with some natural compounds. Food Sci Biotechnol 9 (1):38-42.
Ji J, Zhang W. 2009. Bacterial behaviors on polymer surfaces with organic and inorganic antimicrobial compounds. J Biomed Mater Res A 88A (2):448-53.
Joerger RD. 2007. Antimicrobial films for food applications: A quantitative analysis of their effectiveness. Packag Technol Sci 20 (4):231-73.
Juneja VK, Sofos JN. 2005. Control of foodborne microorganisms. In: Rooney ML, editor. Food Packaging: Principles and Practice. New York: Marcel Dekker Inc. p. 13-281.

878 Kerry JP, O'Grady MN, Hogan SA. 2006. Past, current and potential utilisation of
879 active and intelligent packaging systems for meat and muscle-based products:
880 A review. Meat Sci 74 (1):113-30.
881 Kim JM, Marshall MR, Cornell JA, Preston JF, Wei CI. 1995. Antibacterial activity of
882 carvacrol, citral and gerniol against *Salmonella typhimurium* in culture
883 medium and on fish cubes. J Food Sci 60 (6):1364-8.
884 Kim Y-M, Paik H-D, Lee D-S. 2002. Shelf-life characteristics of fresh oysters and
885 ground beef as affected by bacteriocin-coated plastic packaging film. J Sci
886 Food Agr 82 (9):998-1002.
887 Kloucek P, Smid J, Frankova A, Kokoska L, Valterova I, Pavela R. 2011. Fast
888 screening method for assessment of antimicrobial activity of essential oils in
889 vapor phase. Food Res Int *in press*: DOI: 10.1016/j.foodres.2011.04.044.
890 Knobloch K, Pauli A, Iberl B. 1989. Antibacterial and antifungal properties of
891 essential oil components. J Essent Oil Res 1 (3):119-28
892 Koga T, Hirota N, Takumi K. 1999. Bactericidal activities of essential oils of basil
893 and sage against a range of bacteria and the effects of these essential oils on
894 *Vibrio parahaemolyticus*. Microbiol Res 154 (3):267-73.
895 Koichiro Y. 1993. Keeping freshness by antimicrobial packaging incorporating
896 wasabi extract. Food Sci 11 (35):102-7.
897 Krochta JM, De Mulder-Johnston C. 1997. Edible and biodegradable polymer films.
898 Food Technol 51 (2):61-74.
899 Kuorwel KK, Cran MJ, Sonneveld K, Miltz J, Bigger SW. 2011a. Antimicrobial
900 activity of natural agents against *Saccharomyces cerevisiae*. Packag Technol
901 Sci *in press*: DOI: 10.1002/pts.939.
902 Kuorwel KK, Cran MJ, Sonneveld K, Miltz J, Bigger SW. 2011b. Antimicrobial
903 activity of biodegradable polysaccharide and protein-based films containing
904 active agents. J Food Sci 76 (3):R90-R102.
905 Lachowicz KJ, Jones GP, Briggs DR, Bienvenu FE, Wan J, Wilcock A, Coventry MJ.
906 1998. The synergistic preservative effects of the essential oils of sweet basil
907 (*Ocimum basilicum l.*) against acid-tolerant food microflora. J Appl Microbiol
908 26 (3):209-14.
909 Lambert RJW, Skandamis PN, Coote PJ, Nychas GJ. 2001. A study of the minimum
910 inhibitory concentration and mode of action of oregano essential oil, thymol
911 and carvacrol. J Appl Microbiol 91 (3):453-62.
912 Lau OW, Wong SK. 2000. Contamination in food from packaging material. J
913 Chromatogr A 882 (1):255-70.
914 Lee D-S, Hwang Y, Cho S-H. 1998. Developing antimicrobial packaging film for
915 curled lettuce and soyabean sprouts. Food Sci Biotechnol 7 (2):117-21.
916 Limjaroen P, Ryser E, Lockhart H, Harte B. 2003. Development of a food packaging
917 coating material with antimicrobial properties. J Plastic Film Sheeting 19
918 (2):95-109.
919 Limjaroen P, Ryser E, Lockhart H, Harte B. 2005. Inactivation of *Listeria*
920 *monocytogenes* on beef bologna and Cheddar cheese using polyvinyl-idene
921 chloride films containing sorbic acid. J Food Sci 70 (5):M267-M71.
922 Lin YT, Labbe RG, Shetty K. 2004. Inhibition of *Listeria monocytogenes* in fish and
923 meat systems by use of oregano and cranberry phytochemical synergies. Appl
924 Environ Microbiol 70 (9):5672-8.
925 López-Malo A, Alzamora SM, Palou E. 2002. *Aspergillus flavus* dose-response curves
926 to selected natural and synthetic antimicrobials. Int J Food Microbiol 73 (2-
927 3):213-8.

López-Malo A, Maris Alzamora S, Palou E. 2005. *Aspergillus flavus* growth in the presence of chemical preservatives and naturally occurring antimicrobial compounds. Int J Food Microbiol 99 (2):119-28.
López-Malo A, Barreto-Valdivieso J, Palou E, Martín FS. 2007. Aspergillus flavus growth response to cinnamon extract and sodium benzoate mixtures. Food Control 18 (11):1358-62.
López P, Sánchez C, Batlle R, Nerín C. 2007a. Vapor-phase activities of cinnamon, thyme, and oregano essential oils and key constituents against foodborne microorganisms. J Agric Food Chem 55 (11):4348-56.
López P, Sánchez C, Batlle R, Nerín C. 2007b. Development of flexible antimicrobial films using essential oils as active agents. J Agric Food Chem 55 (21):8814-24.
Lorenzo D, Loayza I, Dellacassa E. 2003. Composition of the essential oils from leaves of two *Hedyosmum spp.* and bolovia. Flavour Frag J 18 (1):32-5.
Marques A, Encarnação S, Pedro S, Nunes M. 2008. In vitro antimicrobial activity of garlic, oregano and chitosan against *Salmonella enterica*. World J Microbiol Biotechnol 24 (10):2357-60.
Matan N, Rimkeeree H, Mawson AJ, Chompreeda P, Haruthaithanasan V, Parker M. 2006. Antimicrobial activity of cinnamon and clove oils under modified atmosphere conditions. Int J Food Microbiol 107 (2):180-5.
Matche RS, Kulkarni G, Raj B. 2006. Modification of ethylene acrylic acid film for antimicrobial activity. J Appl Polym Sci 100 (4):3063-8.
Mauriello G, Ercolini D, La Storia A, Casaburi A, Villani F. 2004. Development of polythene films for food packaging activated with an antilisterial bacteriocin from *Lactobacillus curvatus* 32Y. J Appl Microbiol 97 (2):314-22.
Mauriello G, De Luca E, La Storia A, Villani F, Ercolini D. 2005. Antimicrobial activity of a nisin-activated plastic film for food packaging. Lett Appl Microbiol 41 (6):464-9.
Mazzanti G, Battinelli L, Salvatore G. 1998. Antimicrobial properties of the linalool-rich essential oil of *Hyssopus officinalis L. var decumbens* (Lamiaceae). Flavour Frag J 13 (5):289-94.
Mehyar GF, Al-Qadiri HM, Abu-Blan HA, Swanson BG. 2011. Antifungal effectiveness of potassium sorbate incorporated in edible coatings against spoilage molds of apples, cucumbers, and tomatoes during refrigerated storage. J Food Sci 76 (3):M210-M7.
Mejlholm O, Dalgaard P. 2002. Antimicrobial effect of essential oils on the seafood spoilage micro-organism *Photobacterium phosphoreum* in liquid media and fish products. Lett Appl Microbiol 34 (1):27-31.
Miltz J, Passy N, Mannhwim CH. 1995. Trends and applications of active packaging systems. In: Ackerman P, Jagerstad M, Ohlsson T, editors. Food and Packaging Materials - Chemical Interaction. Cambridge: The Royal Society of Chemistry. p. 201-10.
Miltz J, Rydlo T, Mor A, Polyakov V. 2006. Potency evaluation of a dermaseptin s4 derivative for antimicrobial food packaging applications. Packag Technol Sci 19 (6):345-54.
Natrajan N, Sheldon BW. 2000. Efficacy of nisin-coated polymer films to inactivate *Salmonella typhimurium* on fresh broiler skin. J Food Protect 63 (9):1189-96.
Nedorostova L, Kloucek P, Urbanova K, Kokoska L, Smid J, Urban J, Valterova I, Stolcova M. 2011. Antibacterial effect of essential oil vapours against different

strains of *Staphylococcus aureus*, including MRSA. Flavour Frag J *in press*: DOI: 10.1002/ffj.2068.

Nielsen PV, Rios R. 2000. Inhibition of fungal growth on bread by volatile components from spices and herbs, and the possible application in active packaging, with special emphasis on mustard essential oil. Int J Food Microbiol 60 (2-3):219-29.

Nychas GJE. 1995. Natural antimicrobials from plants. In: Gould GW, editor. New Methods of Food Preservation. London: Blackie Academic & Professional. p. 58-89.

Olasupo NA, Fitzgerald DJ, Narbad A, Gasson MJ. 2004. Inhibition of *Bacillus subtilis* and *Listeria innocua* by nisin in combination with some naturally occuring organic compounds. J Food Protect 67 (3):596-600.

Ouattara B, Simard RE, Piette G, Bégin A, Holley RA. 2000. Inhibition of surface spoilage bacteria in processed meats by application of antimicrobial films prepared with chitosan. Int J Food Microbiol 62 (1-2):139-48.

Oussalah M, Caillet S, Saucier L, Lacroix M. 2006. Antimicrobial effects of selected plant essential oils on the growth of a *Pseudomonas putida* strain isolated from meat. Meat Sci 73 (2):236-44.

Ozdemir M, Floros JD. 2004. Active food packaging technologies. Crit Rev Food Sci Nutr 44 (3):185-93.

Padgett T, Han IY, Dawson PL. 1998. Incorporation of food-grade antimicrobial compounds into biodegradable packaging films. J Food Protect 61 (10):1330-5.

Pauli A. 2001. Antimicrobial properties of essential oil constituents. Int J Aromather 11 (3):126-33.

Periago P, Delgoda B, Fernandez P, Palop A. 2004. Use of carvacrol and cymene to control growth and viability of *Listeria monocytogenes* cells and predictions of survivors using frequency distribution functions. J Food Protect 67 (7):1408-16.

Persico P, Ambrogi V, Carfagna C, Cerruti P, Ferrocino I, Mauriello G. 2009. Nanocomposite polymer films containing carvacrol for antimicrobial active packaging. Polym Eng Sci 49 (7):1447-55.

Prasad G, Kumar A, Singh AK, Bhattacharya AK, Singh K, Sharma VD. 1986. Antimicrobial activity of essential oils of some *Ocimum* species and clove oil. Fitoterapia 57 (6):429-32.

Quintavalla S, Vicini L. 2002. Antimicrobial food packaging in the meat industry. Meat Sci 62 (3):373-80.

Rai MK, Qureshi S, Pandey AK. 1999. In vitro susceptibility of opportunistic *Fusarium* spp. to essential oils. Mycoses 42 (1-2):97-101.

Ramirez MX, Walters KB, Hirt DE. 2005. Relationship between erucamide surface concentration and coefficient of friction of LLDPE film. J Vinyl Addit Technol 11 (1):9-12.

Rardniyom C. 2008. Development of multi-layer films containing natural antimicrobial agents. [PhD dissertation]. Melbourne, Australia: Victoria University. 145 p.

Rardniyom C, Miltz J, Bigger SW, Cran MJ, Sonneveld K. 2008. Parameters affecting the design of antimicrobial films. Proceedings of 16th IAPRI World Conference on Packaging. Bangkok, Thailand, June 8-12.

Raybaudi-Massilia RM, Mosqueda-Melgar J, Martín-Belloso O. 2009. Edible alginate-based coating as carrier of antimicrobials to improve shelf-life and safety of fresh-cut melon. Int J Food Microbiol 121 (3):313-27.

Rodríguez-Lafuente A, Nerín C, Batlle R. 2010. Active paraffin-based paper packaging for extending the shelf life of cherry tomatoes. J Agric Food Chem 58 (11):6780-6.

Rodríguez A, Nerín C, Batlle R. 2008. New cinnamon-based active paper packaging against Rhizopusstolonifer food spoilage. J Agric Food Chem 56 (15):6364-9.

Rojas-Graü MA, Solvia-Fortuny R, Martín-Belloso O. 2009. Edible coatings to incorporate active ingredients to fresh-cut fruits: A review. Trends Food Sci Technol 20 (10):438-47.

Rokchoy S, Suppakul P, Jinkarn T. 2009. Antimicrobial effects of vanillin coated solution for coating paperboard intended for packaging bakery products. Asian J Food Agro-Ind 4 (2):138-47.

Roller S, Seedhar P. 2002. Carvacrol and cinnamic acid inhibit microbial growth in fresh-cut melon and kiwifruit at 4°C and 8°C. Lett Appl Microbiol 35 (5):390-4.

Rooney ML. 1995. Active food packaging. London: Blackie Academic & Professional. p. 260.

Rupika LAS, Sonneveld K, Miltz J, Bigger SW. 2005. Development and evaluation of low-density polyethylene-based antimicrobial food packaging polymers containing thymol and carvacrol. Proceedings of 22nd IAPRI Symposium on Packaging. Campinas, Brazil, May 22-24.

Rupika LAS, Miltz J, Sonneveld K, Cran MJ, Bigger SW. 2006. Effectiveness of antimicrobial films containing a natural antimicrobial agent. Proceedings of 15th IAPRI World Conference on Packaging. Tokyo, Japan, October 2-5.

Rupika LAS, Sonneveld K, Bigger SW, Cran MJ, Miltz J. 2008. Modelling microbial inactivation by films containing thymol or carvacrol. Proceedings of 16th IAPRI World Conference on Packaging. Bangok, Thailand, June 8-12.

Rydlo T, Miltz J, Mor A. 2006. Eukaryotic antimicrobial peptides: Promises and premises in food safety. J Food Sci 71 (9):R125-R35.

Sagdiç O, Özcan M. 2003. Antibacterial activity of turkish spice hydrosols. Food Control 14 (4):141-3.

Salleh E, Muhamadi l, Khairuddinr N. 2007. Inhibition of *Bacillus subtilis* and *Escherichia coli* by antimicrobial starch-based film incorporated with lauric acid and chitosan. Proceedings of 3rd CIGR Section Vl International Symposium on Food and Agricultural Products: Processing and Innovation. Naples, ltaly,

Sanla-Ead N, Jangchud A, Chonhenchob V, Suppakul P. 2011. Antimicrobial activity of cinnamaldehyde and eugenol and their activity after incorporation into cellulose-based packaging films. Packag Technol Sci *in press*: DOI: 10.1002/pts.952.

Scannell AGM, Hill C, Ross RP, Marx S, Hartmeier W, Arendt EK. 2000. Development of bioactive food packaging materials using immobilised bacteriocins Lacticin 3147 and Nisaplin®. Int J Food Microbiol 60 (2-3):241-9.

Schelz Z, Molnar J, Hohmann J. 2006. Antimicrobial and antiplasmid activities of essential oils. Fitoterapia 77 (4):279-85.

Seaberg AC, Labbe RG, Shetty K. 2003. Inhibition of *Listeria monocytogenes* by elite clonal extracts of oregano (*Origanum vulgare*). Food Biotechnol 17 (2):129-49.

Sikkema J, Bont JAM, Poolman B. 1995. Mechanisms of membrane toxicity of hydrocarbons. Microbiol Rev 59 (2):201-22.

Silveira MFA, Soares NFF, Geraldine RM, Andrade NJ, Gonçalves MPJ. 2007. Antimicrobial efficiency and sorbic acid migration from active films into pastry dough. Packag Technol Sci 20 (4):287-92.

Simon JE, Quinn J, Murray RG. 1990. Basil: A source of essential oils. In: Janick J, Simon JE, editors. Advances in New Crops Research. Portland, Oreg.: Timber Press. p. 484-9.

Singh G, Marimuthu P, De Heluani CS, Catalan CAN. 2006. Antioxidant and biocidal activities of *Carum nigrum* (seed) essential oil, oleoresin, and their selected components. J Agric Food Chem 54 (1):174-81.

Singh TK, Drake MA, Cadwallader KR. 2003. Flavour of Cheddar cheese: A chemical and sensory perspective. Comp Rev Food Sci Food Safety 2 (4):139-62.

Siragusa GR, Cutter CN, Willett JL. 1999. Incorporation of bacteriocin in plastic retains activity and inhibits surface growth of bacteria on meat. Food Microbiol 16 (3):229-35.

Sivropoulou A, Papanikolaou E, Nikolaou C, Kokkini S, Lanaras T, Arsenakis M. 1996. Antimicrobial and cytotoxic activities of *Origanum* essential oils. J Agric Food Chem 44 (5):1202-5.

Skandamis PN, Nychas G-JE. 2001. Effect of oregano essential oil on microbiological and physico-chemical attributes of minced meat stored in air and modified atmospheres. J Appl Microbiol 91 (6):1011-22.

Smith-Palmer A, Stewart J, Fyfe L. 2001. The potential application of plant essential oils as natural food preservatives in soft cheese. Food Microbiol 18 (4):463-70.

Smith J, Hoshino J, Abe Y. 1995. Interactive packaging involving sachet technology. In: Rooney ML, editor. Active Food Packaging. London: Blackie Academic & Professional. p. 143-72.

Suhr KI, Nielsen PV. 2003. Antifungal activity of essential oils evaluated by two different application techniques against rye bread spoilage fungi. J Appl Microbiol 94 (4):665-74.

Suppakul P, Sonneveld K, Miltz J, Bigger SW. 2003a. Antimicrobial properties of basil and its possible application in food packaging. J Agric Food Chem 51 (11):3197-207.

Suppakul P, Sonneveld K, Miltz J, Bigger SW. 2003b. Active packaging technologies with an emphasis on antimicrobial packaging and its applications. J Food Sci 68 (2):408-20.

Suppakul P. 2004. Study of antimicrobial polymeric packaging films containing basil extracts. [PhD dissertation]. Melbourne, Australia: Victoria University 259 p.

Suppakul P, Miltz J, Sonneveld K, Bigger SW. 2006. Characterization of antimicrobial films containing basil extracts. Packag Technol Sci 19 (5):259-68.

Suppakul P, Sonneveld K, Bigger SW, Miltz J. 2008. Efficacy of polyethylene-based antimicrobial films containing principal constituents of basil. LWT - Food Sci Technol 41 (5):779-88.

Suppakul P, Sonneveld K, Bigger SW, Miltz J. 2011a. Diffusion of linalool and methylchavicol from polyethylene-based antimicrobial packaging films. LWT - Food Sci Technol 44 (9):1888-93

Suppakul P, Sonneveld K, Bigger SW, Miltz J. 2011b. Loss of AM additives from antimicrobial films during storage. J Food Eng 105 (2):270-6.

Tassou C, Koutsoumanis K, Nychas GJE. 2000. Inhibition of Salmonella enteritidis and Staphylococcus aureus in nutrient broth by mint essential oil. Food Res Int 33 (3-4):273-80.

Tassou CC, Drosinos EH, Nychas G-JE. 1996. Inhibition of resident microbial flora and pathogen inocula on cold fresh fish fillets in olive oil, oregano, and lemon juice under modified atmosphere or air. J Food Protect 59 (1):31-4.

Tepe B, Daferera D, Sokmen M, Polissiou M, Sokmen A. 2004. *In vitro* antimicrobial and antioxidant activities of the essential oils and various extracts of *Thymus eigii*. J Agric Food Chem 52 (5):1132-7.

Tsigarida E, Skandamis P, Nychas G-JE. 2000. Behaviour of *Listeria monocytogenes* and autochthonous flora on meat stored under aerobic, vacuum and modified atmosphere packaging conditions with or without the presence of oregano essential oil at 5^{o}c. J Appl Microbiol 89 (6):901-9.

Tunç S, Duman O. 2011. Preparation of active antimicrobial methyl cellulose/carvacrol/montmorillonite nanocomposite films and investigation of carvacrol release. LWT - Food Sci Technol 44 (2):465-72.

Ultee A, Gorris LGM, Smid EJ. 1998. Bactericidal activity of carvacrol towards the food-borne pathogen *Bacillus cereus*. J Appl Microbiol 85 (2):211-8.

Ultee A, Kets EPW, Smid EJ. 1999. Mechanisms of action of carvacrol on the food-borne pathogen *Bacillus cereus*. Appl Environ Microbiol 65 (10):4606-10.

Ultee A, Slump RA, Steging G, Smid EJ. 2000. Antimicrobial activity of carvacrol towards *Bacillus cereus* on rice. J Food Protect 63 (5):620-4.

Ultee A, Smid EJ. 2001. Influence of carvacrol on growth and toxin production by *Bacillus cereus*. Int J Food Microbiol 64 (3):373-8.

Ultee A, Bennik MHJ, Moezelaar R. 2002. The phenolic hydroxyl group of carvacrol is essential for action against the food borne pathogen *Bacillus cereus*. Appl Environ Microbiol 68 (4):1561-8.

Vartiainen J, Skytta E, Ahvenainen-Rantala R, Enqvist J. 2003a. Antimicrobial and barrier properties of LDPE films containing imazalil and EDTA. J Plastic Film Sheeting 19 (4):249-61.

Vartiainen J, Skytta E, Enqvist J, Ahvenainen R. 2003b. Properties of antimicrobial plastics containing traditional food preservatives. Packag Technol Sci 16 (6):223-30.

Vermeiren L, Devlieghere F, Beest MV, Kruijf ND, Debevere J. 1999. Developments in the active packaging of foods. Trends Food Sci Technol 10 (3):77-86.

Vermeiren L, Devlieghere F, Debevere J. 2002. Effectiveness of some recent antimicrobial packaging concepts. Food Addit Contam 19 (suppl.):163-71.

Viuda-Martos M, Ruiz-Navajas Y, Fernandez-Lopez J, Perez-Alvarez J. 2008. Antibacterial activity of different essential oils obtained from spices widely used in mediterranean diet. Int J Food Sci Technol 43 (3):526-31.

Vojdani F, Torres AJ. 1989. Potassium sorbate permeability of methylcellulose and hydroxypropyl methylcellulose multi-layer films. J Food Process Pres 13 (6):417-30.

Wan J, Wilcock A, Coventry MJ. 1998. The effect of essential oils of basil on the growth of *Aeromonas hydophila* and *Pseudomonas fluorescens*. J Appl Microbiol 84 (2):152-8.

Weng Y-M, Hotchkiss JH. 1992. Inhibition of surface molds on cheese by polyethylene film containing the antimycotic imazalil. J Food Protect 58 (5):367-9.

Weng Y-M, Hotchkiss JH. 1993. Anhydrides as antimycotic agents added to polyethylene films for food packaging. Packag Technol Sci 6 (3):123-8.

Weng Y-M, Chen M-J. 1997. Sorbic anhydride as antimycotic additive in polyethylene food packaging films. LWT - Food Sci Technol 30 (5):485-7.

Weng Y-M, Chen M-J, Chen W. 1999. Antimicrobial food packaging materials from poly(ethylene-co-methacrylic acid). LWT - Food Sci Technol 32 (4):191-5.

Wu J-G, Wang P-J, Chen SC. 2010. Antioxidant and antimicrobial effectiveness of catechin-impregnated PVA–starch film on red meat. J Food Qual 33 (6):780-801.

Youdim KA, Deans SG. 2000. Effect of thyme oil and thymol dietary supplementation on the antioxident status and fatty acid composition of the ageing rat brain. J Nutr 83 (1):87-93.

Zaika LL. 1988. Spices and herbs: Their antimicrobial activity and its determination. J Food Safety 9 (2):97-118.