Bioactivity of essential oils: a review on their interaction with food components

Marianne Perricone, Ersilia Arace, Maria R. Corbo, Milena Sinigaglia and Antonio Bevilacqua*

Department of the Sciences of Agriculture, Food and Environment, University of Foggia, Foggia, Italy

INTRODUCTION

Synthetic antimicrobial agents and chemical food preservatives have been used since ancient times as an effective method for controlling food spoilage. Nowadays, consumer concerns toward chemical preservatives determine an increasing interest on some natural antimicrobials, like essential oils (EOs). EOs are liquid preparations produced from plant materials (flowers, buds, seeds, leaves, twigs, bark, herbs, wood, fruits, and roots) of temperate or warm countries, like Mediterranean and tropical areas. Only a few of them are solid or resinous at room temperature; they are limpid, soluble in lipids or in organic solvents, with a generally lower density than that of water, with a pale yellow to emerald green or blue to dark brownish red color (Burt, 2004; Gutierrez). These extracts were referred as EOs by Paracelsus von Hohenheim in 16th, who used the term “Quinta essentia” to design the active component of a drug and from the Latin essentia comes the term “essential” (Guenther, 1948).

EOs play a major role in plants and act as antibacterials, antivirals, antifungals, insecticides, and protect the plants from herbivores. It is possible to list ca. 3000 EOs, but only 300 of them are used in perfumes and make-up products (creams, soaps, etc.), sanitary products, dentistry, agriculture, as preservatives, and flavor additives for foods, as fragrances for household cleaning products and industrial solvents and as natural remedies (as mixtures with vegetal oil in massages or in baths, in aromatherapy, etc.; Burt, 2004; Gutierrez et al., 2008).

EOs can be produced by expression, fermentation, enfleurage, or extraction, although hydro-distillation is the most common method (Speranza and Corbo, 2010). EOs and their active components possess antiviral, antimycotic, antitoxicogenic, and insecticidal properties. Table 1 reports the most important EOs, their aroma notes, and the target bacteria.

Even though several studies were performed in vitro to assess antibacterial and antifungal properties of EOs, only few studies reported on their bioactivity in vivo; food components (fats, carbohydrates, proteins, salts) and pH could reduce the antimicrobial effects of EOs in food systems. In fact, the same effect observed in vitro is achieved in food matrix only with higher concentrations (Tyagi et al., 2014).

The scope of this review is to highlight the interactions of EOs with proteins, carbohydrates, oils, NaCl, and pH as a preliminary step to optimize food applications; the last section deals with the different protocols to assess their bioactivity both under in vivo and in vitro conditions.

Keywords: essential oils, antibacterial, bioactivity, food composition, methods

CHEMICAL COMPOSITION AND MECHANISM OF ACTION OF EOs

Essential oils are mixtures of 20–60 components at quite different concentrations, with some compounds at fairly high concentrations (20–70%), and others in trace amounts. The components at high concentrations (terpenes, terpenoids, molecules with an aromatic ring) play a major role in the antimicrobial/biological effect of EOs (Bakkali et al., 2008).

Some important compounds of EOs are mono and sesquiterpenes, carbohydrates, phenols, alcohols, ethers, aldehydes, and ketones (Speranza and Corbo, 2010). Phenolic compounds have also been recognized as bioactive components (Tabassum and Vidyasagar, 2013).

Essential oils with aldehydes or phenols as major components (cinnamaldehyde, citral, carvacrol, eugenol, or thymol) are the most effective, followed by EOs containing terpene alcohols (Bassolé and Juliani, 2012). EOs with ketones or esters (β-myrcene, α-thujone, or geranyl acetate) possess a lower activity (Dormans and Deans, 2000; Barros et al., 2009).

Although the major components of EOs are very important for their biological activity, minor components play a

Table 1

| Essential Oil | Aroma Notes | Target Bacteria |
|--------------|-------------|----------------|
| Eucalyptus | Fresh, minty, medicinally | Gram-positive and Gram-negative bacteria |
| Melaleuca | Fresh, lemony | Gram-positive and Gram-negative bacteria |
| Thymus | Sharp, camphoraceous | Gram-positive and Gram-negative bacteria |
| Rosemary | Fresh, resinous | Gram-positive and Gram-negative bacteria |

www.frontiersin.org
significant role, as they can strengthen the effects of major components, though antagonistic, and additive effects have also been observed (Bassolé and Juliani, 2012). Table 2 reports some examples of combination of EOs toward a wide range of bacteria.

The composition of EOs relies upon the harvesting seasons and the geographical sources (Burt, 2004), as well as from the part of plant, e.g., EO from the seeds of coriander (Coriandrum sativum L.) shows a different composition from EO of cilantro, produced from immature leaves (Delaquis et al., 2002).

Table 1 | Antimicrobial and aroma characteristics of essential oils (EOs; modified from Ayala-Zavala et al., 2009).

| Essential oil | Major volatile constituents | Antimicrobial effect against | Aroma notes |
|---------------|----------------------------|----------------------------|-------------|
| Garlic root   | Methyl disulfide, allyl sulfide, allyl disulfide, allyl trisulfide, trimethylene trisulfide, allyl tetrasulfide | *Bacillus cereus*, *Escherichia coli*, *Shigella* spp., *Vibrio parahaemolyticus*, *Yersinia enterolitica*, *Salmonella enterica* serovars *Enteritidis*, *Infantis*, *Typhimurium*, *B. subtilis*, *Enterococcus faecalis* Alternaria alternata | Pungent, spice |
| Cinnamon leaf | Cinnamaldehyde, eugenol, copaene, β-caryophyllene | *E. coli*, *Pseudomonas aeruginosa*, *Ent. faecalis*, *Staphylococcus aureus*, *Staph. epidermidis*, methicillin-resistant *Staph. aureus*, Klebsiella pneumoniae, *Salmonella* sp., *Vibrio parahaemolyticus* | Sweet, wood, spice |
| Thyme         | Thymol, p-cymene, γ-terpinene, linalool | *B. cereus*, *Clostridium botulinum*, *Ent. faecalis*, *E. coli*, *Staph. aureus*, *Listeria monocytogenes*, *Aspergillus flavus*, *A. niger*, *K. pneumoniae*, *Ps. aeruginosa*, *Salmonella* sp. | Spice, citrus, wood |
| Oregano       | Sabinyl monoterpenes, terpinen-4-ol, γ-terpinene, carvacrol, thymol | *B. cereus*, *B. subtilis*, *C. botulinum*, *Ent. faecalis*, *E. coli*, *Staph. aureus*, *A. niger*, *L. monocytogenes*, *Ps. aeruginosa*, *Salmonella* sp. | Spice, herb |
| Clove         | Eugenol, eugenyl acetate, caryophyllene | *B. brevis*, *B. subtilis*, *Cl. botulinum*, *Ent. faecalis*, *Candida* spp., *A. flavus*, *A. niger*, *E. coli*, *K. pneumoniae*, *Ps. aeruginosa*, *Staph. aureus*, *Salmonella* spp., *L. monocytogenes* | Sweet, spice, wood |
| Basil         | Linalool, methylchavicol, eugenol, methyl eugenol, methyl cinnamate, 1,8-cineole, caryophyllene | *B. brevis*, *E. coli*, *A. flavus*, *A. niger*, *Ent. faecalis*, *E. coli*, *K. pneumoniae*, *Ps. aeruginosa*, *Staph. aureus* | Fresh, sweet, herb, spice |
| Coriander     | 2(E)-decanal, 2(E)dodecenal, linalool | *E. coli*, *L. monocytogenes*, *Lactobacillus plantarum*, *Staph. aureus* | Sweet, flower, spice, citrus |
| Citrus peel   | Limonene, linalool, citral | *A. niger*, *A. flavus*, *Penicillium verrucosum*, *P. chrysogenum* | Sweet, citrus |
| Laurel        | 1,8-cineole, α-terpinyl acetate, linalool, methyl eugenol | *Staph. aureus*, *B. cereus*, *Ent. faecalis* | Fresh, herb, spice |
| Ginger        | β-sesquiphellandrene, zingiberene | *A. flavus*, *A. niger*, *Ent. faecalis*, *E. coli*, *K. pneumoniae*, *Ps. aeruginosa*, *Staph. aureus* | Pungent, spice |
| Rosemary      | Borneol, verbeneone, camphor, α-pinene, 1,8-cineole | *A. flavus*, *A. niger*, *Ent. faecalis*, *E. coli*, *K. pneumoniae*, *Ps. aeruginosa*, *Staph. aureus*, *L. monocytogenes*, *Lb. plantarum*, *Salmonella* spp., *B. cereus* | Fresh, herb, resinous |
| Peppermint    | Menthol, menthone, menthy acetate, menthofuran | *B. brevis*, *Staph. aureus*, *Vibrio cholerae*, *Ent. faecalis*, *E. coli*, *K. pneumoniae*, *Ps. aeruginosa*, *A. flavus*, *A. niger* | Fresh, herb |
| Pair                   | Organism                                | Methods     | Interaction |
|-----------------------|-----------------------------------------|-------------|-------------|
| Thymol/carvacrol      | Staph. aureus, Ps. aeruginosa           | Half dilution | Additive    |
|                       | E. coli                                 | Checkerboard | Synergism   |
|                       | S. aureus, B. cereus, E. coli           | Checkerboard | Antagonism  |
|                       | Staph. aureus, Ps. aeruginosa           | Mixture     | Additive    |
|                       | E. coli                                 | Checkerboard | Additive    |
|                       | Salmonella Typhimurium                  | Mixture     | Synergism   |
| Thymol/eugenol        | E. coli                                 | Checkerboard | Synergism   |
| Carvacrol/eugenol     | E. coli                                 | Checkerboard | Synergism   |
|                       | Staph. aureus, B. cereus, E. coli       | Checkerboard | Antagonism  |
| Carvacrol/Cymene      | B. cereus                               | Mixture     | Synergism   |
| Carvacrol/linalool    | L. monocytogenes                        | Checkerboard | Synergism   |
| Menthol/Geraniol/Menthol/Thymol | Staph. aureus, B. cereus       | Mixture | Synergism   |
| Cinnamaldehyde/Carvacrol | E. coli                                      | Checkerboard | Additive    |
|                       | Salmonella Typhimurium                  | Mixture     | Synergism   |
| Cinnamaldehyde/Thymol | E. coli                                 | Checkerboard | Synergism   |
|                       | Salmonella Typhimurium                  | Mixture     | Synergism   |
| Cinnamaldehyde/Eugenol | Staphylococcus spp., Micrococcus spp., Bacillus spp., Enterobacter spp. | Mixture | Additive    |
| O. vulgare/O. officinalis | Staph. epidermidis, Staph. aureus, B. subtilis, E. coli, Proteus vulgaris, Ps. aeruginosa | Mixture | Additive    |
| O. vulgare/T. vulgaris | B. cereus, E. coli, Ps. aeruginosa      | Checkerboard | Additive    |
| Cymbopogon citratus/C. giganteus | E. coli, L. monocytogenes, Sh. dysenteriae, Staph. aureus, Salmonella Typhimurium | Checkerboard | Synergism, additive |

Essential Oils are lipophiles, thus they can easily enter cells, disrupt the membrane and/or permeabilize it. The most important signs of membrane permeabilization are the loss of ions and the reduction of potential, the collapse of proton pump and the depletion of ATP pool (Bakkali et al., 2008).

In eukaryotic cells, EOs cause depolarisation of mitochondrial membranes, influence Ca\(^{2+}\) channels and reduce pH gradient, affecting the proton pump and the ATP pool (Bakkali et al., 2008). The membrane becomes abnormally permeable resulting in leakage of radicals, cytochrome c, calcium ions, and proteins. Permeabilization of outer and inner mitochondrial membranes causes apoptosis and necrosis and finally cell death (Armstrong, 2006; Speranza and Corbo, 2010); in addition, EOs can cause the coagulation of cytoplasm and some damages to lipids and proteins (Burt, 2004).

Intrinsic and extrinsic conditions can be responsible of susceptibility and resistance of pathogens (Bajpai et al., 2012). It is not possible to propose a general hit for the susceptibility/resistance to EOs; however, Speranza and Corbo (2010) suggested some milestones:

- Gram-negative bacteria appear more resistant. This higher resistance could be attributed to the outer membrane.
- Lactic acid bacteria (LAB) are the most resistant Gram-positive bacteria. This resistance was attributed to ATP generation by substrate level phosphorylation.
- Among the Gram-negative bacteria, pseudomonads show high resistance to these antimicrobials.
- Essential oils are generally more active toward yeasts.

**ANTIBACTERIAL ACTIVITY OF EOs IN FOOD SYSTEMS**

The bioactivity of EOs might be reduced by certain food components (fats, carbohydrates, proteins, water, salt, antioxidants, preservatives, other additives) and pH (Glass and Johnson, 2004; Gutierrez et al., 2008); moreover, some extrinsic factors (temperature, packaging in vacuum/gas/air, characteristics of microorganisms) play a crucial role (Skandamis and Nychas, 2000; Smith-Palmer et al., 2001). Different studies reported higher levels of bioactivity at acidic pHs, as at low pH EOs behave in a more hydrophobic way and enter more easily cells (Negi, 2012).
High concentrations of fats and/or proteins in foodstuffs may protect bacteria, as they could provide a protective layer and absorb EOs, thus decreasing their concentration and effectiveness in the aqueous phase; on the other hand, high water, and/or salt levels appear to facilitate the action of EOs (Smith-Palmer et al., 2001; Carson and Riley, 2003).

Gutierrez et al. (2008) studied the effect of food ingredients (potato starch-0, 1, 5, or 10%; beef extract-1.5, 3, 6, or 12%; sunflower oil-0, 1, 5, or 10%) and pH (4–7) on the antimicrobial efficacy of oregano and thyme. They focused on both the lag phase and the maximum specific growth rate of *L. monocytogenes*. Starch and sunflower oil exerted a negative effect on the biological activity of EOs, whilst proteins affected it in a positive way; finally, the highest activity was found at pH 5.

Cava et al. (2007) studied the antimicrobial activity of cinnamon and clove EOs against *L. monocytogenes* in milk and found that the biological activity was reduced by fat; these results are in agreement with the effects of EOs in full-fat and in low-fat soft cheeses (Smith-Palmer et al., 2001).

The effect of EOs could be reduced by increasing the amount of complex sugars (starch), whilst glucose and other simple sugars acted in a different way, thus EO application should be orientated to food products containing more simple sugars than complex carbohydrates (Gutierrez et al., 2008, 2009).

Another key factor for the biological activity of EOs is the physical structure of foods, which may limit and affect the antibacterial activity; e.g., *Salmonella Typhimurium* was inoculated in a broth and in a gelatine gel, both containing an EO. In the gel the effect of EO was reduced for its limited diffusion (Speranza and Corbo, 2010).

In many cases EO combinations showed additive effects, e.g., Gutierrez et al. (2008) combined oregano and basil or thyme toward *Escherichia coli* and *Pseudomonas aeruginosa*, with majoram toward *E. coli*, and majoram and thyme mixed with basil, rosemary or sage against *L. monocytogenes*. Moreover, Lambert et al. (2001) suggested that carvacrol and thymol acted as additive terms against *Staphylococcus aureus* and *P. aeruginosa*.

Some EOs, even at low concentrations, can have a negative impact on the sensory attributes, due to their low breakpoint for perception (Lv et al., 2011); therefore the need of higher concentrations in food is highly unfortunate and limits their application to spicy foods. An alternative approach is the use of EOs into active packaging, either encapsulated in polymers of edible and biodegradable coatings or entrapped in sachets able to slowly release the active compounds on food surface or in the headspace (Pelissari et al., 2009; Sánchez-González et al., 2011). Cerisuelo et al. (2014) tested some passive, active, and nanocomposite multilayer films; the performances of EVOH were low, as this matrix was not able to retain the active compounds. However, the inclusion of bentonite nanoparticles into EVOH active coatings increased the release rate and the retention ability.

In addition, another way to minimize the organoleptic effects of EOs is the preparation of nanoemulsions; this approach positively affects both the stability and the antimicrobial activity (Donsi et al., 2011).

Tyagi and Malik (2012) and Tyagi et al. (2012) proposed the use of EOs in the vapor phase, by combining bactericidal volatiles and ionizing sources. Since active compounds of EOs are highly volatile, the presence in gaseous form facilitates the solubilization of lipophilic monoterpenes in cell membranes.

Some papers focused on the combination of EOs with other treatments as reported by Tyagi et al. (2012, 2013): they tested lemon grass and mentha oils in combination with mild thermal treatment (55°C). Hence, this strategy significantly reduces oil dose requirement, offers a very useful synergy, as the increase of the temperature increases the amount of oil in the vapor phase, thus it enhances its antimicrobial activity.

### SOME CASE-STUDIES DEALING WITH THE APPLICATION OF EOs IN FOODS

#### MEAT AND MEAT PRODUCTS

Eugenol and coriander, clove, oregano, and thyme oils were used to control pathogens and autochthonous spoilage flora in meat, as they caused a marked initial reduction in the viable cell number (Speranza and Corbo, 2010). As reported elsewhere fat reduced the bioactivity of EOs in meat products; in fact, some authors reported that thyme oil reduced significantly bacterial population of *L. monocytogenes* in zero and low-fat (90 g/Kg) beef hot-dogs, but not in full-fat hot-dogs (260 g/Kg; Lemay et al., 2002; Singh et al., 2004).

The new consumer preference toward hurdle technology suggests the potentiality of combining different elements to preserve foods; following this approach, Choulia et al. (2007) combined oregano EO and modified atmosphere packaging (MAP) for the prolongation of the shelf life of fresh breast chicken meat, stored at 4°C. The effect of oregano EO (0.1 and 1% w/w) was evaluated in combination with two kinds of MAP [30:70 CO2:N2 (MAP1) and 70:30 CO2:N2 (MAP2)]. Samples treated with 1% oregano oil and packaged under both MAPs did not attain the critical level of cell count (7 log cfu/g) during a 25 day storage period.

#### SEAFOOD PRODUCTS

As reported for meat, fat reduced the bioactivity of EOs in fish. Speranza and Corbo (2010) reported that the effect of oregano oil at 0.05% (v/w) toward *Photobacterium phosphoreum* was stronger on cod filets than on salmon (a fatty fish). Some authors (Corbo et al., 2008; Del Nobile et al., 2009a) proposed combinations of EOs to improve the microbial stability of fish burgers. A mix containing 0.11% of thymol, 0.10% of grapefruit seed extract (GFSE) and 0.12% of lemon extract was proposed, as it increased the shelf life of fish burgers (stored under refrigeration and packaged in air) by 40%. Moreover the combined effect of the EOs and MAP was evaluated; samples were packaged in air and in three different gas mix compositions: 30:40:30 O2:CO2:N2, 50:50 O2:CO2, and 5:95 O2:CO2. The proposed packaging strategies inhibited the growth of mesophilic bacteria.

#### VEGETABLES AND FRUITS

In vegetables the antimicrobial activity of EOs is enhanced by a decrease of storage temperature and pH (Smith-Palmer et al., 2001). The shelf life of unpasteurised fruit juices is limited by microbial enzymatic spoilage; moreover, these products could be contaminated by some pathogens. Some EOs could be used to
Table 3 | Different methods used to test the antimicrobial activity of EOs (Burt, 2004).

| Purpose                                      | Test method                                      |
|----------------------------------------------|--------------------------------------------------|
| Screening for antibacterial activity        | Disk diffusion (solid or vapor diffusion assay)  |
| Determination of the strength of antibacterial properties | Agar wells                                       |
| Determination of rapidity and duration of antimicrobial activity | Broth dilution (visible growth, optical density/turbidity, absorbance, viable count, colorimetric and conductance/conductivity/impedance) |
| Evaluation of the physical effects          | Time-kill analysis/survival curves                |

was used in combination with orange oil for a validation in milk. The effect of terpineol oil was affected by fat content, showing a microbial reduction of 7 log cfu/ml in skimmed milk, 4 log cfu/ml in low butterfat milk and 3 log cfu/ml in whole milk (Fisher and Phillips, 2008). Another approach was proposed by Bevilacqua et al. (2007) who studied the possibility of prolonging the shelf life of caprese salad using MAP (65:30:5 N₂:CO₂:O₂) in combination with thymol. The combination of thymol dipping and MAP prolonged the shelf life by 8 days, without negative effects on the sensory quality and on the growth kinetics of LAB.

CEREAL-BASED PRODUCTS
Natural active compounds were also applied to fresh pasta. Del Nobile et al. (2009b) used thymol, lemon extract, chitosan, and GFSE at different concentrations (2000 and 4000 ppm) to improve the microbiological stability of refrigerated amaranth-based fresh pasta. The oils were tested against mesophilic and psychrotrophic bacteria, total coliforms, Staphylococcus spp., yeasts, and molds. Chitosan and GFSE were the most promising compounds, whereas lemon extract was the less effective.

METHODS TO ASSESS THE ANTIMICROBIAL ACTIVITY OF EOs
The methods to assess the antimicrobial activity of EOs could be grouped in three classes: diffusion, dilution, or auxographic methods (Rios et al., 1988). Tables 3 and 4 report an overview of the most common protocols used to test the bioactivity of EOs. The most widely used test is NCCLS method, generally designed to test antibiotics but modified for testing EOs (Hammer et al., 1999; NCCLS, 2000); a filter disk is impregnated with the antimicrobial agent, placed on the surface of inoculated agar plates and an inhibition of growth is observed after incubation. This test is generally used for screening purposes, although its results rely upon many factors, like the method used to extract the EO from plant material, the volume of inoculum, the physiological phase of the microorganism, the kind of culture medium, pH, incubation time, and temperature. A modification of the method is the use of wells instead of a paper disk.

However, many papers propose direct contact between microorganism and antimicrobial agent; whereas, an alternative method is the use of essential oil in the vapor phase (Lopez et al., 2005; Tyagi et al., 2012). In the vapor diffusion assays a filter disk

Table 4 | Terms used in antibacterial activity testing reported in literature (from different literature sources).

| Term                              | Definition presented in literature                                      |
|-----------------------------------|--------------------------------------------------------------------------|
| Minimum inhibitory concentration (MIC) | Lowest concentration resulting in the maintenance or in the reduction of inoculum viability |
| Minimum bactericidal concentration (MBC) | Lowest concentration required for the complete inhibition up to 48 h |
| Bacteriostatic concentration     | Lowest concentration inhibiting visible growth                           |
| Bactericidal concentration       | Concentration resulting in a significant decrease in inoculum viability (>90%) |
|                                  | Lowest concentration able to kill at least the 99.9% of the target.       |
|                                  | Lowest concentration able to inhibit microbial growth, without killing the test organism |
|                                  | Lowest concentration able to kill/inactivate the test microorganism      |
is impregnated with the antimicrobial agent and placed on the medium-free cover of each Petri dish, while microorganism target are inoculated on agar surface; the Petri dishes were then sealed using sterile adhesive tape.

Other methods are the micro-dilution approaches (dilution in broth or in agar, evaluation of microbial growth by plate counting or by indirect indices).

REFERENCES

Armstrong, J. S. (2006). Mitochondrial membrane permeabilization: the sine qua non for cell death. *BioEssays* 28, 253–260. doi: 10.1002/bies.20370

Ayala-Zavala, J. F., Gonzalez-Aguilar, G. A., and Del Toro-Sánchez, L. (2009). Enhancing safety and aroma appealing of fresh-cut fruits and vegetables using the antimicrobial and aromatic power of essential oils. Concise reviews and hypotheses in food science. *J. Food Sci. 74*, 84–91. doi: 10.1111/j.1750-3841.2009.01294.x

Bajpai, V. K., Baeck, K., and Kang, S. C. (2012). Control of *Salmonella* in foods by using essential oils: a review. *Food Res. Int. 45*, 722–734. doi: 10.1016/j.foodres.2011.04.052

Bakkali, F., Averbeck, S., Averbeck, D., and Idaomar, M. (2008). Biological effects of essential oils – a review. *Food Chem. Toxicol. 46*, 446–475. doi: 10.1016/j.fct.2007.09.106

Barros, J. C., Conceição, M. L., Gomes Neto, N. J., Costa, A. C. V., Siqueira Júnior, I. P., Baulão Júnior, J. D., et al. (2009). Interference of *Organism vulgaris* essential oil on the growth and some physiological characteristics of *Staphylococcus aureus* strains isolated from foods. *IWT-Food Sci. Technol. 42*, 1139–1143. doi: 10.1016/j.jwst.2009.01.010

Bassolé, I. H. N., and Juliani, H. R. (2012). Essential oils in combination and their antimicrobial properties. *Molecules* 17, 3899–4006. doi: 10.3390/molecules17043989

Bevilacqua, A., Corbo, M. R., and Sinigaglia, M. (2007). Combined effects of mod-
Hypotheses in food science and safety issues for food application—a review. *J. Int. J. Food Microbiol. 94*, 223–233. doi: 10.1016/j.ijfoodmicro.2004.03.022

Carson, C. F., and Riley, T. V. (2003). Non-antibiotic therapies for infectious diseases. *Commun. Dis. Intell. Q. Rep. 27*, S143–S146.

Cava, R., Nowak, E., Taboada, A., and Marin-Iniesta, F. (2007). Antimicrobial activity of clove and cinnamon essential oils against *Listeria monocytogenes* in pasteurized milk. *J. Food Prot. 70*, 720–722.

Burt, S. (2004). Essential oils: their antimicrobial properties and potential applications in foods: a review. *Int. J. Food Microbiol. 94*, 223–233. doi: 10.1016/j.ijfoodmicro.2004.03.022

Donsi, A., Annunziata, M., Sessa, M., and Ferrari, G. (2011). Nanocapsulation of essential oils to enhance their antimicrobial activity in foods. *IWT-Food Sci. Technol. 44*, 1908–1914. doi: 10.1016/j.jwst.2011.03.003

Dormans, H. J. D., and Deans, S. G. (2000). Antimicrobial agents from plants: antibacterial activity of plant volatile oils. *J. Appl. Microbiol. 88*, 308–316. doi: 10.1046/j.1365-2672.2000.00969.x

Fisher, K., and Phillips, G. (2008). Potential antimicrobial uses of essential oils in food: is citrus the answer? *Trends Food Sci. Technol. 19*, 156–164. doi: 10.1016/j.tifs.2007.11.006

Glass, K. A., and Johnson, E. A. (2004). Antagonistic effect of fat on the antibotulinal activity of food preservatives and fatty acids. *Food Microbiol. 21*, 675–682. doi: 10.1016/j.fm.2004.03.002

Guenther, E. (1948). *The Essential Oils*, Vol. 1. New York: David van Nostrand Co. Inc.

Gutierrez, J., Barry-Ryan, C., and Bourke, P. (2008). Biological effects of essential oils—a review. *Food Chem. Toxicol. 46*, 446–475. doi: 10.1016/j.fct.2007.07.006

Glass, J., Chouquette, J., Delaquis, P. J., Gariépy, C., Rodrigue, N., and Saucier, L. (2002). Antimicrobial effect of natural preservatives in a cooked and acidified chicken meat model. *Int. J. Food Microbiol. 78*, 217–226. doi: 10.1016/S0168-1605(02)00114-4

Lopez, P., Sánchez, C., Battler, R., and Nerian, C. (2005). Solid– and vapor-phase antimicrobial activities of six essential oils: susceptibility of selected foodborne bacterial and fungal strains. *J. Agric. Food Chem. 53*, 6939–6946. doi: 10.1021/jf050709v

Lv, F., Liang, H., Yuan, Q., and Li, C. (2011). In vitro antimicrobial effects and mechanism of action of selected plant essential oil combinations against four food related microorganism. *Food Res. Int. 44*, 3057–3064. doi: 10.1016/j.foodres.2011.07.030

NCCLS. (2000). *Methods for Dilution Antimicrobial Susceptibility Tests for Bacteria that Grow Aerobically: Approved Standard*, NCCLS Document M7-A5, 5th Edn. Wayne, PA: NCCLS.

Neri, P. S. (2012). Plant extracts for the control of bacterial growth: efficacy, stability, and safety issues for food application—a review. *J. Int. J. Food Microbiol. 156*, 7–17. doi: 10.1016/j.ijfoodmicro.2012.03.006

Pelissari, F. M., Grossmann, M. V. E., Yasahita, P., and Pined, E. A. G. (2009). Antimicrobial, mechanical, and barrier properties of casa Sava starch-chitosan films incorporated with oregano essential oil. *J. Agric. Food Chem. 57*, 7499–7504. doi: 10.1021/jf9002363

Raybaudi-Massilia, R. M., Mosqueda-Melgar, J., and Martin-Belloso, O. (2006). Antimicrobial activity of essential oils on *Salmonella enteridis, Escherichia coli*, and *Listeria innocua* in fruit juices. *J. Food Prot. 69*, 1579–1586.

Raybaudi-Massilia, R. M., Mosqueda-Melgar, J., Sobrino-Lopez, A., Soliva-Fortuny, R., and Martin-and Belloso, O. (2009). Use of malic acid and other quality stabilizing compounds to assure the safety of fresh cut "fuji" apples by inactivation of *Listeria monocytogenes*, *Salmonella Enteritidis*, and *Escherichia coli*, in fruit juices. *J. Food Prot. 69*, 1579–1586.

Rios, J. L., Recio, M. C., and Villar, A. (1988). Screening methods for natural antimicrobial products with antimicrobial activity: a review of the literature. *J. Ethnopharmacol. 23*, 127–149. doi: 10.1016/0378-8741(88)90001-3

Rojas-Grau, M. A., Raybaudi-Massilia, R. M., Soliva-Fortuny, R. C., Avena-Bustillos, R. J., McHugh, T. H., and Martin-Belloso, O. (2007). Apple puree alginate edible coatings as carrier of antimicrobial agents to prolong shelf-life of fresh cut apple slices: a review. *Postharvest Biol. Technol. 45*, 254–264. doi: 10.1016/j.postharvbio.2007.01.017

Sánchez-González, L., Vargas, M., González-Martínez, C., Chiralt, A., and Chafé, M. (2011). Use of essential oils in bioactive edible coatings: a review. *Food Eng. Rev. 3*, 1–16. doi: 10.1007/s12393-010-9031-3
Singh, A., Singh, R. K., Bhunia, A. K., and Singh, N. (2004). Efficacy of plant essential oils as antimicrobial agents against *Listeria monocytogenes* in hot-dogs. *J. Food Sci. Technol.* 36, 787–794. doi: 10.1016/S0023-6438(03)00112-9

Skandamis, P. N., and Nychas, G. J. E. (2000). Development and evaluation of a model predicting the survival of *Escherichia coli* O157:H7 NCTC 12900 in homemade eggplant salad at various temperatures, pHs and oregano essential oil concentrations. *Appl. Environ. Microbiol.* 66, 1646–1653. doi: 10.1128/AEM.66.4.1646-1653.2000

Smith-Palmer, A., Stewart, J., and Fyfe, L. (2001). The potential application of plant essential oils as natural food preservatives in soft cheese. *Food Microbiol.* 18, 463–470. doi: 10.1006/fmic.2001.0415

Speranza, B., and Corbo, M. R. (2010). “Essential oils for preserving perishable foods: possibilities and limitations,” in *Application of Alternative Food Preservation Technologies to Enhance Food Safety and Stability*, eds A. Bevilacqua, M. R. Corbo, and M. Sinigaglia (Sharjah: Bentham Publisher), 35–57.

Tabassum, N., and Vidyasagar, G. M. (2013). Antifungal investigations on plant essential oils. A review. *Int. J. Pharm. Pharmacol.* 5, 19–28.

Tyagi, A. K., Gottardi, D., Malik, A., and Guerzoni, M. E. (2013). Anti-yeast activity of mentha oil and vapours through in vitro and in vivo (real fruit juices) assays. *Food Chem.* 137, 108–114. doi: 10.1016/j.foodchem.2012.10.015

Tyagi, A. K., Gottardi, D., Malik, A., and Guerzoni, M. E. (2014). Chemical composition, in vitro anti-yeast activity and fruit juice preservation potential of lemon grass oil. *J. Food Sci. Technol.* 57, 731–737. doi: 10.1007/jfst.2014.02.004

Tyagi, A. K., and Malik, A. (2012). Bactericidal action of lemon grass oil vapors and negative air ions. *Innov. Food Sci. Emerg. Technol.* 13, 169–177. doi: 10.1016/j.ifset.2011.09.007

Tyagi, A. K., Malika, A., Gottardi, D., and Guerzoni, M. E. (2012). Essential oil vapour and negative air ions: a novel tool for food preservation. *Trends Food Sci. Technol.* 26, 99–113. doi: 10.1016/j.tifs.2012.02.004

**Conflict of Interest Statement:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Received: 25 April 2014; accepted: 21 January 2015; published online: 09 February 2015.

Citation: Perricone M, Arace E, Corbo MR, Sinigaglia M and Bevilacqua A (2015) Bioactivity of essential oils: a review on their interaction with food components. *Front. Microbiol.* 6:76. doi: 10.3389/fmicb.2015.00076

This article was submitted to Food Microbiology, a section of the journal Frontiers in Microbiology.

Copyright © 2015 Perricone, Arace, Corbo, Sinigaglia and Bevilacqua. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) or licensor are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.