Beneficial Effects of Spices in Food Preservation and Safety

Davide Gottardi¹, Danko Bukvicki², Sahdeo Prasad³ and Amit K. Tyagi¹, ³*

¹ Department of Agricultural and Food Sciences, Alma Mater Studiorum, University of Bologna, Cesena, Italy; ² Faculty of Biology, Institute of Botany and Botanical Garden "Jevremovac", University of Belgrade, Belgrade, Serbia; ³ Division of Cancer Medicine, Department of Experimental Therapeutics, The University of Texas MD Anderson Cancer Center, Houston, TX, USA

Spices have been used since ancient times. Although they have been employed mainly as flavoring and coloring agents, their role in food safety and preservation have also been studied in vitro and in vivo. Spices have exhibited numerous health benefits in preventing and treating a wide variety of diseases such as cancer, aging, metabolic, neurological, cardiovascular, and inflammatory diseases. The present review aims to provide a comprehensive summary of the most relevant and recent findings on spices and their active compounds in terms of targets and mode of action; in particular, their potential use in food preservation and enhancement of shelf life as a natural bioingredient.

Keywords: inflammatory diseases, spices, food preservation, disease prevention, antimicrobial

INTRODUCTION

Plant, animal, and microbes represent an unlimited source of compounds with medicinal properties (Tajkarimi et al., 2010). Since ancient time, humans are using spices as nutritional agents (Kaefer and Milner, 2008). According to the U.S. Food and Drug Administration (FDA), spice is an "aromatic vegetable substance in the whole, broken, or ground form, the significant function of which in food is seasoning rather than nutrition" and from which "no portion of any volatile oil or other flavoring principle has been removed" (Sung et al., 2012).

More than 100 varieties of spices are produced throughout the world. Asia is the main leader for the production of spices, particularly of cinnamon, pepper, nutmeg, cloves, and ginger, while Europe grows mainly basil, bay leaves, celery leaves, chives, coriander, dill tips, thyme, and watercress. In America, instead, pepper, nutmeg, ginger, allspice, and sesame seed are mainly produced (Prasad et al., 2011).

Although spices have been used (mostly dried seed, fruit, root, bark, or vegetative material) for rituals, cosmetics and perfumery, their flavoring, coloring and, especially, preservative properties have founded wide applications both in the traditional food preparations and in the food industry. In fact, many compounds isolated from spices (Table 1) have shown antimicrobial activity against some of the most common microorganisms that affect the food quality and shelf life (Tajkarimi et al., 2010). The introduction of spices through the meals has various beneficial effects as well. For instance, they can stimulate the secretion of saliva, promote the digestion, prevent from cold and influenza, and reduce nausea and vomiting (Ravindran, 2002; Sultana et al., 2010). In this manuscript we provide an overview on spices and their constituent as a natural food preservatives in vitro and in vivo.

IMPORTANCE OF SPICES

Spices have been important to mankind since the beginning of history. Several mythological evidence including “Epic of Gilgamaesh,” and the “Bagavad Gita,” suggest their use for several
### TABLE 1 | Antimicrobial potential of phytochemicals (spices) for food preservation; *In vitro* study.

| Scientific/Common name | Major compounds | Microorganisms/Model | References |
|------------------------|-----------------|----------------------|------------|
| 1. Acacia victoriae (Wattleseed) | Avicin, Saponins | *S. cerevisiae* | Simons et al., 2006 |
| 2. Aframomum melegueta (Grains of paradise) | Gingerol | *A. niger*, *Salmonella* spp., *E. coli* | Nneka and Jude, 2012 |
| 3. Aframomum kororima (Korarima) | 1,8-Cineole, Sabinene, Nerolidol | *A. flavus*, *Penicillium expansum* | Hymete et al., 2006 |
| 4. Allium sativum (Garlic) | Diallyl sulfide, Allicin | *St. aureus*, *S. Typhi*, *B. cereus*, *B subtilis*, *E. coli*, *Ls. monocytogenes*, *Klebsiella* spp. | Eyob et al., 2008, Doherty et al., 2010 |
| 5. Allium schoenoprasum (Chives) | Allicin, Diallyl sulfides | *E. coli* | Yadav and Singh, 2004 |
| 6. Alkanna tinctoria (Alkanet) | Pulegone, 1,8-Cineole, —– | —– | Ozer et al., 2010 |
| 7. Alpinia galanga (Greater galanga) | Galango-isoflavonoid, β-Sitosterol, Galangin, β-Caryophyllene, β-Seilene | *S. Typhimurium*, *St. aureus*, *B. subtilis*, *A. niger* | Kaushik et al., 2011 |
| 8. Amomum subulatum (Black cardamom) | —– | *E. coli*, *P. aeruginosa* | Bhatt et al., 2014 |
| 9. Angelica archangelica (Angelica) | α-Pinene, δ-3-Carene, Limonene, P. cephei, Eugenol | *E. coli*, *St. aureus* | Fraternale et al., 2014 |
| 10. Anethum graveolens (Dill) | Carvone, Limonene, Myristicin, Anethole, Eugenol | *Clostridium botulinum*, *P. aeruginosa*, *St. aureus*, *Y. Enterococci* | Fraternale et al., 2014 |
| 11. Apium graveolens (Celery seed) | β-Pinene, Camphene, Cumene, Limonene | *St. aureus*, *E. coli* | Baananou et al., 2013 |
| 12. Armoracia rusticana (Scherb) | Isothiocyanate, Catechin, Kaempferol, Quercetin, | *B. subtilis*, *St. aureus* | Mucete et al., 2006 |
| 13. Artemisia dracunculus (Tarragon) | Artemisinin Phenolic acids, Coumarins, Flavonoids, Cumene, Limonene | *St. aureus*, *Ls. monocytogenes* | Peerkam et al., 2014, Ceylan and Fung, 2004 |
| 14. Brassica juncea (Brown mustard) | Isothiocyanate, Diallyl trisulfide, Allyl-isothiocyanate, Allyl- isothiocyanate | *Ls. monocytogenes*, *St. aureus*, *S. entertidts*, *S. veneziana*, *En. homaechei*, *En. cloacae*, *Citrobacter freundii*, *K. pneumoniae*, *En. sakazakii*, *En. amnigenus* | Oboliski et al., 2011 |
| 15. Brassica nigra (Black mustard) | Gallic acid, Rutin, Caffeic acid, Quercetin, Ferulic acid | *E. coli*, *St. aureus* | Sethi et al., 2013 |
| 16. Brassica nigra (Black mustard) | Gallic acid, Rutin, Caffeic acid, Quercetin, Ferulic acid | *E. coli*, *St. aureus* | Sethi et al., 2013 |
| 17. Bunium persicum (Black cumin) | γ-Terpine, Cumarinaldehyde, p-Cymene, Limonene | *B. subtilis*, *St. aureus* | Mazidi et al., 2012 |
| 18. Capsicum annuum (Chilli pepper) | Capsaicin | *St. aureus*, *S. Typhimurium* | Koffi-Nevry et al., 2012 |
| 19. Carum carvi (Caraway) | Carvone, Limonene, Carvacrol, Anethole | *E. coli*, *P. aeruginosa* | Agrahari and Singh, 2014 |
| 20. Cinnamomum aromaticum (Cassia) | Cinnamyl alcohol, Cinnamarin | *E. coli*, *S. Typhimurium*, *Ls. monocytogenes*, *P. aeruginosa*, *S. entertidts* | Frankova et al., 2014, Al-Dhubiab, 2012 |
| 21. Cinnamomum burmannii (Indonesian cinnamon) | Galacturonic acid | *St. aureus*, *E. coli* | Al-Dhubiab, 2012 |
### TABLE 1 | Continued

| Scientific/Common name | Major compounds | Microorganisms/Model | References |
|------------------------|----------------|----------------------|------------|
| 22. Cinnamomum verum (Cinnamon) | Cinnamic aldehyde, Eugenol | *E. coli*, *Ps. fluorescens* | Yadav and Singh, 2004 |
| 23. Citrus hystrix (Kaffir lime) | Limonene, Citronellal, β-Pinene | *E. coli*, *B. cereus* | Unlu et al., 2010 |
| | | *St. aureus* | Naveed et al., 2013 |
| 24. Ceratonia siliqua (Carob tree) | Nonadecane, Heneicosane, Farnesol, Camphor | *Ls. monocytogenes*, *B. cereus*, *St. aureus* | Tabassum and Vizhasagar, 2013 |
| 25. Citrus aurantifolia (Lime) | Limonene, β-Pinene, γ-Terpinene, Citral | *E. coli*, *P. aeruginosa* | Ng et al., 2011 |
| 26. Coriandrum sativum (Coriander) | Dodecenal, 1-Decanol, Ergosterol | *S. epidermidis*, *St. aureus* | Zhu et al., 2011 |
| 27. Crocus sativus (Saffron) | Lauric acid, Hexadecanoic acid, 4-Hydroxy dihydro-2(3H)-furanone, Stigmasterol, Crocetin, Crocin | *E. coli*, *B. subtilis* | Sethi et al., 2013 |
| 28. Curcuma longa (Turmeric) | Curcumin | *S. Typhi*, *Ls. monocytogenes*, *Clostridium spp.*, *St. aureus*, *E. coli*, *B. cereus*, *B. subtilis*, *C. albicans*, *Y. enterocolitica*, *P. notatum*, *S. cerevisiae* | Moghadamtousi et al., 2014 |
| 29. Cuminum cyminum (Cumin) | Cuminal | *B. cereus*, *B. subtilis*, *Ls. monocytogenes*, *C. freundii*, *K. pneumoniae*, *Ps. fluorescens*, *S. enteritidis*, *St. aureus*, *A. niger*, *S. cerevisiae*, *C. albicans* | Radwan et al., 2014 |
| 30. Cymbopogon citrates (Lemon grass) | Citral, Myrcene, Linalool, Farnesol | *E. coli*, *C. albicans* | Ceylan and Fung, 2004 |
| 31. Elettaria cardamomum (Green cardamom) | 1,8-Cineole, Linalool, α-Terpinyl acetate | *B. cereus*, *Ls. monocytogenes*, *St. aureus*, *S. enteritidis*, *P. aeruginosa* | Savan and Kucukbay, 2013 |
| 32. Eruca sativa (Rocket) | Erucic acid, Oleic acid | *S. aureus*, *S. epidermidis*, *P. aeruginosa* | Malli et al., 2007 |
| 33. Eryngium foetidum (Long coriander) | E-2-Dodecanal ("eryngial"), Dodecanolic acid | *St. aureus*, *B. subtilis*, *Ls. monocytogenes* | Shavandi et al., 2012 |
| 34. Ferula asafoetida (Asafoetida) | α-Pinene, α-Terpineol, Azulene | *E. coli*, *B. subtilis*, *P. chrysogenum*, *A. ochraceus* | Divya et al., 2014 |
| 35. Foeniculum vulgare (Fennel) | Anethole | *B. cereus*, *S. enteritidis*, *Y. enterocolitica*, *St. aureus*, *B. subtilis*, *E. coli*, *P. aeruginosa*, *A. niger*, *C. vulgaris*, *Shigella dysenteriae*, *E. coli* | Ceylan and Fung, 2004 |
| 36. Garcinia indica (Kokum) | Garcinol | *E. coli*, *B. cereus*, *St. aureus*, *C. albicans* | Elumalai and Eswaraiah, 2011 |

(Continued)
| Scientific/Common name | Major compounds | Microorganisms/Model | References |
|------------------------|-----------------|----------------------|------------|
| 37. Heracleum persicum (Goipar) | Pimpinellin, Isopimpinellin Bergapten, Isobergapten | C. albicans | Hemati et al., 2010 |
| 38. Hyssopus officinalis (Hyssop) | Isopinocamphone, Terpinen-4-ol Pinocarvone, Carvacrol | E. coli, S. Typhimurium, C. albicans, S. aureus | Di Pasqua et al., 2005; Süleyman et al., 2010 |
| 39. Houttuynia cordata (Chameleon plant) | Aristolactams, Houttuynoside A | S. Typhimurium | Kumar et al., 2014 |
| 40. Illicium verum (Star anise) | Shikimic acid, Anethole Ethyl-cinnamate, 1,8-cineole Camphene, Borneol, Kaempferol Kaempferide | B. cereus | Shan et al., 2007 |
| 41. Kaempferia galanga (Kencur) | Ethyl-cinnamate, 1,8-cineole Camphene, Borneol, Kaempferol Kaempferide | C. albicans, S. aureus | Süleyman et al., 2010 |
| 42. Laurus nobilis (Bay) | 1,8-Cineole, α-Pinene, Limonene 2-Carene | Alternaria alternata, E. coli | Xu et al., 2014 |
| 43. Lavandula angustifolia (Lavender) | 1,8-Cineole, Camphor, Borneole (Lavender) Ocimene, Terpinolene, Camphor | S. aureus, E. coli | Cherrat et al., 2014; Torabbeigi and Azar, 2013 |
| 44. Limnophila aromatic (Finger grass) | Thymol, Carvacrol, flavonoids | M. luteus, Salmonella spp. | Hernández-Hernández et al., 2014 |
| 45. Lippia adoensis (Koseret) | Linalool, Germacrene D | St. aureus, C. albicans, S. cerevisiae | Folashade and Egharevba, 2012 |
| 46. Lippia graveolens (Mexican oregano) | Thymol, Carvacrol, flavonoids | M. luteus, Salmonella spp. | Hernández-Hernández et al., 2014 |
| 47. Maranta arundinacea (Arrowroot) | Ravonoids, terpenoids | E. coli, Ls. monocytogenes, S. enteritidis, St. aureus | Pilau et al., 2011; Rajashekhara et al., 2013 |
| 48. Melissa officinalis (Balm) | Neral, Citronellal, Isomenthone, Menthone, β-Caryophyllene, Carvacrol | Shigella sonnei | Moradkhani et al., 2010 |
| 49. Mentha piperita (Mint) | Menthol, 1,8-cineole | E. coli, P. aeruginosa, St. aureus, Streptococcus faecalis, C. albicans | Sharafi et al., 2010; Saharkhiz et al., 2012; McKay and Blumberg, 2006; Tyagi et al., 2013 |
| 50. Monodora myristica (Calamash nutmeg) | Cymene, α-Phellandrene Germacrene D-4-ol | St. aureus, B. cereus, C. albicans | Owekotono and Ekundayo, 2012; Odoh et al., 2004 |
| 51. Murraya koenigii (Curry leaf) | Murrayanol | | Handral et al., 2012 |
| 52. Myrica gale (Gaile) | Murrayacine, Mahanine, Cymene, β-Elemene, Myrcene, Limonene | St. aureus, B. subtilis, S. cerevisiae, C. albicans | Nakata et al., 2013 |
| 53. Myristica fragrans (Nutmeg) | Myristicin, Sabine, β-Pinene | S. aureus, B. subtilis, P. aeruginosa, A. niger | Gupta et al., 2013b; Radwan et al., 2014 |
| 54. Myrrhis odorata (Cicely) | p-Cymene, α-Terpinene, δ-Cadinene | E. coli, St. aureus, Clostridium spp. | Rancic et al., 2005 |
| Scientific/Common name | Major compounds | Microorganisms/Model | References |
|------------------------|-----------------|----------------------|------------|
| 55. Myrtus communis (Myrtle) | Myrtenyl acetate, 1,8-Cineole, α-Pinene | Ls. monocytogenes | Amensour et al., 2010 |
| 56. Nigella sativa (Black caraway) | Thymoquinone, Nigellone | St. aureus, E. coli, P. aeruginosa | Islam et al., 2012 |
| 57. Ocimum canum | α-Terpineol, Chavicol, Chavibetol | Food spoiling bacteria | Vry Wouatsa et al., 2014 |
| 58. Ocimum basilicum (Basil) | 1,8-Cineole, Linalool, Methyl chavicol | B. subtilis, E. coli, S. Typhimurium, S. aureus, Ls. monocytogenes, Cl. botulinum, Ls. innocua, Ps. fragi, Ps. fluorescens, Yarrowia lipolytica | Shirazi et al., 2014 |
| 59. Olea europaea (Olive) | Oleuropein | B. cereus, E. coli | Faiza et al., 2011 |
| 60. Olax subschorpioidea ———– | ———– | C. albicans, C. tropicalis | Dzoyem et al., 2014 |
| 61. Origanum vulgare (Oregano) | Carvacrol | E. coli, Ls. monocytogenes, S. cerevisiae, Ls. monocytogenes | Siroli et al., 2014b, Lv et al., 2011 |
| 62. Origanum majorana (Marjoram) | ———– | B. subtilis, E. coli | Leeja and Thopil, 2007 |
| 63. Pandanus amaryllifolius (Pandan leaves) | 2-Acetyl-1-pyrroline | E. coli | Routray and Rayaguru, 2010 |
| 64. Petroselinum crispum (Parsley) | Kaempferol, Quercetin | B. cereus, St. aureus, Ls. monocytogenes | Faras et al., 2014, Shahtale et al., 2007 |
| 65. Persicaria odorata (Vietnamese coriander) | β-Caryophyllene, Caryophyllene oxide | St. aureus, E. coli, C. albicans, E. coli | Shavandi et al., 2012, Sasongko et al., 2011 |
| 66. Pimpinella anisum (Anise) | Anethole | A. ochraceus | Krisch et al., 2011 |
| 67. Piper betle (Betel) | Eugenol, Acetyl Eugenol | St. aureus, E. coli, V. cholerae | Prakash et al., 2010, Hoque et al., 2011 |
| 68. Piper capense (Timiz) | β-Pinene, Sabinene | St. aureus | Woguem et al., 2013 |
| 69. Piper guineense (Ashanti pepper) | Lignans, Alkaloids, Flavonoids, Polyphenols | St. aureus, E. coli | Nwinyi et al., 2009, Juliani et al., 2013 |
| 70. Piper nigrum (Black pepper) | Piperine | St. aureus, E. coli, B. cereus, P. aeruginosa | Shiva Rani et al., 2013, Khalil and Siddiqui, 2007 |
| 71. Piper retrofractum (Long pepper) | Piperine | E. coli, P. aeruginosa, A. niger | Khan and Siddiqui, 2007 |
| 72. Polygonum hydropiper (Water-pepper) | Catechin, Polygodial, Quercetin, Hyperin | E. coli, B. subtilis, St. aureus, S. cerevisiae, C. albicans | Moyeenul Huq et al., 2014, Cachet et al., 2009 |
| 73. Quassia amara (Amargo) | Quassin | E. coli, St. aureus | Ajalyeoba and Krebs, 2003, Shabir, 2012 |
| 74. Rhus coriaria (Sumac) | Quercetin, Myricetin, Kaempferol | E. coli, St. aureus, Ls. monocytogenes | Shiva Rani et al., 2013, Khalil and Siddiqui, 2007 |

(Continued)
| Scientific/Common name | Major compounds                                  | Microorganisms/Model                      | References                           |
|------------------------|--------------------------------------------------|-------------------------------------------|--------------------------------------|
| Rosmarinus officinalis | p-Cymene, Linalool, Thymol, γ-Terpinene, Camosic acid, Carnosol | *Brochothrix thermosphacta*               | Jayasena and Jo, 2013                |
| (Rosemary)             |                                                  | *Pseudomonas spp.*                        | Özcan and Chalchat, 2008             |
| Ruta graveolens        | Rutin                                            | *St. aureus, E. coli*                     | De La Torre Torres et al., 2015      |
| (Rue)                  |                                                  |                                           | Hamrad, 2012                          |
| Salvia officinalis     | 1,8-Cineole                                      | *Salmonella sp.*                          | Kumar et al., 2014                   |
| (Sage)                 |                                                  |                                           |                                     |
| Sanguisorba minor      | Rutin                                            | *E. coli, S. aureus*                      | Hayouni et al., 2008                 |
| (Salad burnet)         |                                                  |                                           |                                     |
| Sassafras albidum      | Safrole, Camphor, Methyl eugenol                 | *P. aeruginosa*, *S. Typhimurium*        | Kamdem and Douglas, 2007             |
| (Sassafras)            |                                                  |                                           |                                     |
| Satureja hortensis     | Carvacrol, γ-terpinene, p-cymene                | *B. subtilis, P. aeruginosa,*             | Mihajlov-Krstev et al., 2010         |
| (Summer savory)        |                                                  |                                           |                                     |
| Satureja montana       | Carvacrol, tannins, flavonoids, triterpenes      | *L. monocytogenes*                       | Carraminana et al., 2008             |
| (Winter savory)        |                                                  |                                           |                                     |
| Schinus terebinthifolius| Schinol, Quercetin                               | *St. aureus, B. cereus*                  | Carvalho et al., 2013                |
| (Brazilian pepper)     |                                                  |                                           | Degaspari et al., 2005               |
| Sesamum indicum        | Latifonin, Monor-cerebroside, Soya-cerebroside   | *E. coli*                                | Ogunsola and Faosa, 2014             |
| (Sesame)               |                                                  |                                           |                                     |
| Sinapis alba           | Benzyl isothiocyanate, Benzyl nitrile, thymol   | *E. coli*                                | Al-Gudah et al., 2011                |
| (White mustard)        |                                                  |                                           |                                     |
| Smymium olusatrum      | Sabine, Curzerene, α-Pinene, Cryptone            | — — —                                    | Mokaddem et al., 2010                |
| (Aлександры)          |                                                  |                                           |                                     |
| Syzygium aromaticum    | Eugenol                                          | *E. coli, S. aureus*                     | Yadav and Singh, 2004                |
| (Clove)                |                                                  | *S. anatum, B. cereus*                   | Naveena et al., 2006                 |
| Tasmannia lanceolata   | Polygodial, Saffrole, Guaicol, Calamene, Myristicin, Drimenol | *Ls. monocytogenes*                      | Shani et al., 2007                   |
| (Tasmanian pepper)     |                                                  | *A. niger, C. albicans*                  | Sethi et al., 2013                   |
| Tagetes minuta         | cis-β-ocimene                                    | *E. coli*, *B. cereus*, *B. subtilis*    | Sada et al., 2013                    |
| (Huacatay)             |                                                  | *St. aureus, Ps. aeruginosa, S. Typhry*  | Senatore et al., 2004                |
| T. aureus, C. albicans |                                                  | *C. albicans*                            | Shirazi et al., 2014                 |
| Tasmannia lanceolata   | Polygodial, Saffrole, Guaicol, Calamene, Myristicin, Drimenol | *Ls. monocytogenes*                      | Coff, 2013                           |
| (Tasmanian pepper)     |                                                  | *A. niger, C. albicans*                  | Weerakody et al., 2010               |
| Thymus vulgaris        | Thymol, Cinnamaldehyde                           |                                           | Burt, 2004                           |
| (Thyme)                |                                                  |                                           | Jayasena and Jo, 2013                |
| Thymus capitatus       | Thymol, Camphor, Carvacol                        | *B. cereus, Salmonella sp.*              | Boubaker et al., 2013                |
| (Headed Savory)        |                                                  | *Ls. incola*                             | Bounatirou et al., 2007              |
| Thymus serpyllum       | Thymol, Carvacol                                 | *Ls. monocytogenes*                      | Skrinjar and Nemet, 2009             |
| (Breckland thyme)      |                                                  | *St. aureus, E. coli*                    | Paaver et al., 2008                  |
| Trigonella foenum-graecum| Trigonelline                                    | *E. coli, B. cereus*                     | Upadhyay et al., 2008                |
| (Fenugreek)            |                                                  |                                           | Omezzi et al., 2014                  |
| Trachyspermum ammi     | β-Phellandrene, α-Terpine, Limonene              | *C. albicans, Salmonella spp.*, *S. Typhimurium* | Khan et al., 2010                    |
| (Ajwan)                |                                                  |                                           | Chauhan et al., 2012                 |
| Vanilla planifolia     | Vanillin, Vanillic acid                          | *E. coli, B. cereus*                     | Menon and Nayeem, 2013               |
| (Vanilla)              |                                                  | *S. cerevisiae*, *Zygosaccharomyces bailii, Z. rouxii* | Fitzgerald et al., 2003              |

(Continued)
purposes. Because of their strong preservative quality, spices were also used for embalming. According to Ayurveda, they help to maintain the balance of the body humors (Gupta et al., 2013a). Besides these, spices have been used to change the physical appearance of food. For instance, pepper and turmeric changed the color, appearance, and the taste of food with many health benefits. Ginger, nutmeg and cinnamon improve digestion, considered good for spleen and sore throats (Prasad et al., 2011). Unfortunately, this beneficial effect of spices is not clinically proven. However, traditional practices emphasize the health benefits of spices. Eventually, recent studies highlighted other biological functions of spices, including antimicrobial, antioxidant, and anti-inflammatory (Tajkarimi et al., 2010).

**SPICES FOR FOOD PRESERVATION AND SAFETY**

Food spoilage refers to an irreversible modification in which food becomes not edible or its quality is compromised. Such changes can be driven by different factors, either physical (oxygen, temperature, light) and/or biological (enzymatic activity and microbial growth). Despite the current technologies available in the production chain (for instance freezing, pasteurization, drying, preservatives), it seems impossible to eliminate completely the risk of food spoilage (Gutierrez et al., 2009). Lipid oxidation is one of the main issues of food spoilage. Hence, food industries have applied antioxidants such as butylated hydroxytoluene (BHT) and butylated hydroxyanisole (BHA) to prevent spoilage (Stoilova et al., 2007). However, their safety is doubtful and consumers are progressively demanding natural compounds. For this reason spices represent a potent tool for the food industry, thanks to their natural properties (Hyldgaard et al., 2012). Indeed spices possess antioxidant capacity, mainly due to the presence of phenolic compounds (Figures 1A, B). They exhibit antioxidant property by scavenging free radicals, chelating transition metals, quenching of singlet oxygen, and enhancing the activities of antioxidant enzymes (Rubió et al., 2013). Stoiilova et al. (2007) reported that the CO2 extract of ginger had in vitro activity comparable with that of BHT in inhibiting the lipid peroxidation both at 37 and 80°C. Moreover, pimento and black pepper extracts reduced the formation of acrylamide up to 75 and 50%, respectively, in a model mixture simulating heated potato matrix (180°C for 20 min). Eugenol, the main component of pimento essential oil, limited the formation of acrylamide by 50% (Ciesaróvá et al., 2008). Some other studied antioxidants are: quercetine (dill), capsaicin (red chilli), curcumin (turmeric), carvacrol (oregano, thyme, marjoram), thymol (oregano, thyme), piperine (black pepper), gingerol, etc (ginger, marjoram; Figures 1A, B; Rubió et al., 2013; Przygodzka et al., 2014; Srinivasan, 2014). The relationship between antioxidant properties of spices and food spoilage has been well-documented.

Another issue in food spoilage is the microbial growth. Spices can also exert antimicrobial activity in two ways: by preventing the growth of spoilage microorganisms (food preservation), and by inhibiting/regulating the growth of those pathogenic (food safety; Tajkarimi et al., 2010). Studies regarding in vitro and in vivo antimicrobial activities of spices have been reported in the following sections.

**Antimicrobial Activity In vitro**

Numerous articles published in the last few decades have described the antimicrobial activities of spices in vitro. Extracts of entire plants, or part of them, obtained with diverse solvents (such as ethanol, methanol, ethyl acetate, and water) have been tested against microbes (Tajkarimi et al., 2010). Their essential oils or active compounds, alone or in combination, were also used to test the activity against different microbes (Singh et al., 2007; Weerakkody et al., 2010; Bassolé and Juliani, 2012). Disc-diffusion, drop-agar-diffusion, broth microdilution,
and direct-contact technique in agar represent the most common methods utilized for screening (Tyagi and Malik, 2010a, 2011).

According to these reports, spices possess a very wide spectrum of activity against Gram-positive and Gram-negative bacteria, yeasts and molds (Tajkarimi et al., 2010; Table 1). Alves-Silva et al. (2013) reported that the bush-basil essential oils have antimicrobial activity against *Listeria innocua*, *Serratia marcescens*, *Pseudomonas fragi*, *P. fluorescens*, *Aeromonas hydrophila*, *Shewanella putrefaciens*, *Achromobacter denitrificans*, *Enterobacter amnigenus*, *En. gergoviae*, and *Alcaligenes faecalis*, and against the yeasts *Yarrowia lipolytica*, *Saccharomyces cerevisiae*, *Candida zeylanoides*, *Debaryomyces Hansenii*, and *Pichia carsonii*. Moreover, they were able to inhibit molds such as *Mucor racemosus* and *Penicillium chrysogenum*. In the same study, celery and coriander essential oils also showed a very similar antimicrobial activity against the tested strains.

Although the antimicrobial activity of spices may vary according to the types of spice (origin and bioactive compounds), different bacteria can react in different ways (Hyldgaard et al., 2012). Oregano essential oil showed higher antimicrobial activity against *Listeria monocytogenes* compared to *Escherichia coli* (Siroli et al., 2014b). Huacatay and basil essential oils were
FIGURE 1 | Continued
active against *Staphylococcus aureus* and *Bacillus subtilis* (Shirazi et al., 2014). Essential oil of angelica roots were effective against *Clostridium difficile*, *Cl. perfringens*, *Enterococcus faecalis*, *Eubacterium limosum*, *Peptostreptococcus anaerobius*, and in a lower extent against *E. coli* and *Bacteroides fragilis* (Fraternelle et al., 2014). *Nigella sativa* extracts were more effective on *S. aureus* (5th day inhibition zone 34 mm) as compared to *E. coli* (5th day inhibition zone, 13 mm) and *P. aeruginosa* (5th day inhibition zone, 30 mm; Islam et al., 2012). *Rosmarinus officinalis* essential oil showed a strong antimicrobial effect against *Ls.* *monocytogenes* and *S. aureus* compared with *E. coli* (Jordan et al., 2013). A list of spices and their effects on most relevant bacteria is reported in Table 1.

Spices, essential oils and extracts have also been known for their anti-fungal activity (Table 1; Tajkarimi et al., 2010). Huacatay and basil essential oils were active against *Candida albicans* (Shirazi et al., 2014). Radwan et al. (2014) reported that among 22 common spice extracts, turmeric, and nutmeg extracts were the most active against different plant pathogens belonging to the genus *Colletotrichum*. In another study, where 23 spice extracts were studied, *Oxal subscorpioides* extract showed the highest antifungal activity, particularly against *C. albicans* and *C. tropicalis* (Dzoyem et al., 2014). A reduction of mycelial growth and inhibition of conidial germination and aflatoxin production by *A. flavus* were described by Nerilo et al. (2016) when 150, 10 and 15 µg/mL of ginger EO were applied, respectively. Ferreira et al. (2013) also reported a decrease (99.9 and 99.6%) of aflatoxin B1 and B2 when 0.5% of turmeric EO was employed while the same EO completely inhibited the biomass of *Fusarium graminearum* and its zearalenone production, at 3.5 and 3 mg/mL, respectively (Kumar et al., 2016).

Finally, antiviral activity of Mexican oregano against some viruses (i.e., acyclovir-resistant herpes simplex virus type 1 (ACVR-HHV-1), human respiratory syncytial virus (HRSV), and human rotavirus) has been reported (Pilau et al., 2011). Overall, it is difficult to predict how microorganisms are susceptible. In fact, spics constituents may impact several targets, such as microorganisms cell membrane, enzymes, and/or their genetic material (through the modulation of specific genes; Tajkarimi et al., 2010; Tyagi and Malik, 2010b,c; Hyldgaard et al., 2012).
Enhancement of the Antimicrobial Activity *In vitro*

To enhance the antimicrobial potential of spices or their constituents, the use of mixed extracts or natural compounds having different origins have been reported (Bassolé and Juliani, 2012). In most of the cases spices showed synergistic activities/effects. For instance, the antimicrobial activity of basil, oregano, bergamot, and perilla essential oils alone or in combinations, were tested. Basil and oregano essential oils alone had MICs of 1.25 and 0.625 µL/mL against *E. coli*, respectively, while their values were 0.313 µL/mL when used in combination. The MIC values against *S. aureus* for basil and bergamot EOs alone were for both 1.25 µL/mL, whereas the MICs of the two essential oils decreased to 0.313–0.156 µL/mL when combined, indicating higher antimicrobial activity. MICs of oregano and bergamot essential oils were 0.625 and 1.25 µL/mL against *B. subtilis*, respectively, whereas 0.313 µL/mL was determined for combined effect. Finally, the MIC values of oregano and perilla were 0.625 µL/mL for both against *S. cerevisiae*, while the mixture needed MICs of 0.313–0.156 µL/mL (Lv et al., 2011). In another study, Tabanelli et al. (2014) demonstrated the additive effect of citral and linalool against *S. cerevisiae*. In fact, linalool (250 mg/L) reduced markedly the amount of citral needed for the same effect (from around 150 to 50 mg/L). However, Tejeswini et al. (2014) reported antagonistic effects when cinnamaldehyde was combined with clove essential oils for molds inhibition.

The use of spice oils together with other preservation techniques has been also assessed. For example, low pressure atmosphere enhanced the susceptibility of *E. coli* and *S. enteritidis* to oregano, lemongrass or cinnamon essential oils *in vitro*. In particular, the MIC of cinnamon vapors for *S. enteritidis* decreased from 0.512 to 0.128 µL/mL (Frankova et al., 2014). Tabanelli et al. (2014) reported that the decrease of αw potentiated the antimicrobial effect of citral (but not linalool) while lower pH favored the antimicrobial power of linalool (but not citral) against *S. cerevisiae*. Some other hurdle technologies were also used for the enhancement of antimicrobial potential of essential oils. Tyagi and Malik (2010a, 2011, 2012) described the enhancement in antimicrobial potential of essential oils in combination of negative air ions (NAI) against food spoilage microorganisms.

Antimicrobial Potential in Real Food Model System (*In Vivo*)

Numerous natural compounds of spices with defined antimicrobial properties have been isolated. However, *in vitro* studies represent only one part of the use of active compounds as preservatives in food. Moreover, their physical and biochemical properties have been changed in real food systems due to the complexity of the food matrices (Tajkarimi et al., 2010). Therefore, whether spices or their components have the potential to inhibit the food spoilage and act as a food preservative has been determined in different studies.

As summarized in Table 2, the use of spices as preservatives has been assessed in multiple foods: meat, fish, dairy products, vegetables, rice, fruit, and animal food (Tajkarimi et al., 2010; Jayasena and Jo, 2013). Hernández-Ochoa et al. (2014) reported that cumin and clove essential oils inhibited the growth of total bacteria by 3.78 log CFU/g when used on meat samples for 15 days at 2°C. The antimicrobial activity of different spice extracts in raw chicken meat during storage for 15 days at 4°C was also studied. It has been found that the treatment of raw chicken meat with extracts of clove, oregano, cinnamon, and black mustard was effective against microbial growth (Radha et al., 2014). Essential oils of marjoram and coriander showed above 50% protection of chickpea seed from *Aspergillus flavus* infestation (Prakash et al., 2012). In an *in vivo* assay with cherry tomatoes (*Lycopersicon esculentum*), bay oil was effective against *Alternaria alternata* infection (Xu et al., 2014). In another experiment, Da Silva et al. (2014) treated fresh Tuscan sausages with bay leaf essential oil. Comparing to the non-treated control, the essential oil was able to reduce the population of total coliforms (reduction of 2.8 log CFU/g) and extended the shelf life for 2 days.

Although several studies proved possible applications for spices and their derivatives as food preservatives, only few of them are currently applied on the market. For instance, rosemary is already employed for its preservative properties in meat products. Essential oil of rosemary has been used not only for its flavoring compounds but also for its antimicrobial and antioxidant activity. In fact, carnosic acid, one of its main component, is not only antimicrobial but it possesses an antioxidant activity higher than the common food additives, butylated hydroxytoluene (BHT), and butylated hydroxyanisole (BHA; De La Torre Torres et al., 2015).

Allyl isothiocyanate (AITC), a bioactive organosulfur compound found in cruciferous, plants, such as mustard, is known for its anticarcinogenic properties. It has been tested for effectiveness in preservation of fresh beef, sliced raw tuna and cheese. It possesses a strong antimicrobial activity against *E. coli* O157:H7, Salmonella enterica serovar Montevideo, *S. enterica* ser. Typhimurium, *P. corrugata*, *Campylobacter jejuni*, *St. aureus*, and *Ls. monocytogenes*. Moreover it has the generally recognized as safe (GRAS) status provided by the regulatory agencies of U.S. However, its application is sometimes limited because of its poor aqueous solubility, instability at high temperature, and susceptibility to degradation by nucleophilic molecules (Kim et al., 2002; Li et al., 2015).
**TABLE 2** | Antimicrobial potential of phytochemicals (spices) for food preservation; *In vivo* study.

| Scientific/Common name | Real food models | References |
|------------------------|------------------|------------|
| 1. Allium sativum       | Prevent infections of *L. acidophilus*, *E. coli* and *Aeromonas hydrophila* in poultry meat | Yadav and Singh, 2004 |
| 2. Artemisia dracunculus| Inhibit growth *St. aureus* and *E. coli* in cheese and *Aeromonas hydrophila* in poultry meat | Raeisi et al., 2012 |
| 3. Boesenbergia rotunda | Retard the growth of total viable counts of food pathogen bacteria bacteria in Chinese sausage | Kingchaiyaphum and Rachtanapun, 2012 |
| 4. Brassica nigra       | Reduce microbial growth in raw chicken meat | Radha et al., 2014 |
| 5. Cinnamomum verum    | Potential bio preservative of banana, vegetables, dairy products against *Aspergillus* spp., *Salmonella* spp., | Sessou et al., 2012 |
| 6. Citrus hystrix      | Inhibit the growth food pathogen bacteria in Chinese sausage | Kingchaiyaphum and Rachtanapun, 2012 |
| 7. Coriandrum sativum  | Inhibit the growth of *Ls. monocytogenes* in minced beef meat | Prakash et al., 2012 |
| 8. Cuminum cyminum    | Cumin seed oil protect stored protection of wheat and chickpea against *Aspergillus* spp. | Kedia et al., 2014 |
| 9. Cymbopogon citratus | Inhibit the growth *B. cereus*, *S. Typhimurium* and *St. aureus* in refrigerated chicken patties and inhibition of *Pseudomonas* spp. in rabbit meat | Hayam et al., 2013 |
| 10. Cinnamomum cassia | Raw chicken meat in Fresh sliced apples reduces natural microflora and inoculated *Ls. innocua* | Patrignani et al., 2015 |
| 11. Eryngium foetidum  | Reduce the growth of *Ls. monocytogenes* in pineapple juice | Ngang et al., 2014 |
| 12. Laurus nobilis     | Bay essential oil reduce the population of total coliforms in fresh sausages Protects cherry tomatoes against *Alternaria alternata* infection | Da Silveira et al., 2014 |
| 13. Mentha piperita    | *Mentha* essential oil inhibit *S. cerevisiae* growth in fruit (orange/apple) juice-potential natural food preservative | Tyagi et al., 2013 |
| 14. Olea europaea      | Antibacterial effect against *E. coli*, *P. aeruginosa*, *S. aureus* and *K. pneumoniae* in shrimp/seafood industry | Ali et al., 2014 |
| 15. Origanum vulgare   | Inhibit the growth of *L. monocytogenes*, *Aeromonas hydrophila* and *E. coli* O157:H7 in meat, eggplant salad inhibition of *Pseudomonas* spp. in rabbit meat effectively inhibited the growth of *Salmonella* spp. in chicken meat effective against microbial growth in raw chicken meat in Fresh sliced apples reduces natural microflora and inoculated *Ls. innocua* | Tajkarimi et al., 2010, Burt, 2004, Jayasena and Jo, 2013, Radha et al., 2014, Patrignani et al., 2015, Patrignani et al., 2015, Patrignani et al., 2015, Patrignani et al., 2015 |
| 16. Origanum majorana | Protection of chickpea seed from *A. flavus* infestation | Prakash et al., 2012 |
| 17. Ocimum basilicum   | Inhibit the growth of *S. enteritidis* in fermented pork sausage | Rattanachaikunsopon and Phumkhachorn, 2008 |
| 18. Piper nigrum       | Oil and oleoresins control microbial growth in orange juice | Kapoor et al., 2014 |
| 19. Rosmarinus officinalis | Inhibit the growth of *Ls. monocytogenes*, *Aeromonas hydrophila* and *E. coli* O157:H7 in meat inhibition effect on *Ls. monocytogenes* in liver pork sausage inhibit *Ls. monocytogenes*, *Y. enterocolitica* and *A. Hydrophila* in iceberg lettuce control the natural microflora and inhibit *Ls. monocytogenes*, *E. coli* in Lamb's lettuce | Tajkarimi et al., 2010, Tajkarimi et al., 2010, Patrignani et al., 2015, Patrignani et al., 2015, Patrignani et al., 2015 |
| 20. Salvia officinalis | Inhibit food spoilage in dairy products and *Salmonella* spp. in minced beef meat | Tajkarimi et al., 2010 |
| 21. Satureja montana   | Control the growth of foodborne bacteria/improve quality of minced pork | Tajkarimi et al., 2010 |

(Continued)
in the use of spices and their active compounds in food. In fact, sometimes MIC values were three or four times higher than those estimated in vitro, have been applied to have a measurable or stable antimicrobial effect in vivo. This aspect can dramatically affect the physical characteristics and organoleptic properties of the food products. To overcome these issues, several strategies have been exploited for the enhancement of antimicrobial potential of spices in vivo.

The synergistic effect of spices together with their constituents or other natural products has been tested. Water extracts of clove, cinnamon, and oregano were applied, alone (10 mg/L) or in combination (3.3 g/L each), in raw chicken meat and several characteristics were followed during storage for 15 days at 4°C. The mixture of the three extracts had the strongest impact on the bacterial load due to the synergistic actions of antimicrobial compounds present in the mixed spices (Radha et al., 2014). Sirolı et al. (2014a) examined citral, carvacrol, citron essential oil, hexanal and 2-(E)-hexenal, alone (250 mg/L) or in combination (125 + 125 mg/L, except for the combination of citron essential oil/carvacrol, 200 + 50 mg/L, respectively), to sanitize minimally processed apples. The treatment with citral/2-(E)-hexenal and hexanal/2-(E)-hexenal maintained a good retention of color parameter within the 35 days and there were no yeast spoilage in any treated sample. Gabriel and Pineda (2014) studied the effect of different concentrations of vanillin and licorice root extract (LRE) on the mild heat decimal reduction times (D55-values) of a cocktail of E. coli O157:H7 in young coconut liquid endosperm. They found that the combined effect was most significant only at concentrations above 250 and 210 mg/L, respectively for vanillin and LRE. The efficacy of thymol (0.1% w/w) in combination with sodium lactate (1 and 2% v/w) was evaluated in fish patty samples stored at 4°C for 5 days. The presence of thymol plus 2% of sodium lactate had a synergetic effect against S. enterica ser. Typhimurium to enhance the safety of dairy beverages. The maximum synergistic effect was achieved by 10 kV/cm–3000 µs PEF treatment with 5% (w/v) cinnamon. The maximum inactivation level (1.97 log cycles) was achieved at 50 kV/cm–700 µs plus 5% cinnamon. Patrignani et al. (2013) enhanced the effect of high-pressure homogenization (HPH) treatment (100 MPa for 1–8 successive passes) with citral into inoculated apricot juices, extending their shelf life in turn. Abriouel et al. (2014), instead, potentiated the effect of high hydrostatic pressure (HHP) on brined olives using thyme and rosemary essential oils. In other cases, novel technologies have been used to preserve the functional compounds. For instance, the use of AITC can be limited by its poor aqueous solubility, degradation by nucleophilic molecules, high volatility, and strong odor. Koa et al. (2012) masked the odor and volatility of AITC through its microencapsulation with Arabic.

### Table 2 (Continued)

| Scientific/Common name | Real food models | References |
|------------------------|-----------------|------------|
| 23. Syzygium aromaticum | Inhibit the growth of Ls. monocytogenes in mozzarella cheese, meat and bovine ground meat | Tajkarimi et al., 2010 |
|                        | reduced total bacteria in meat samples | De Oliveira et al., 2013 |
|                        | effective against microbial growth in raw chicken meat | Hernández-Ochoa et al., 2014 |
| 24. Thymus vulgaris     | Slight effect on Ps. putida in cooked shrimp sausages | Radha et al., 2014 |
|                        | inhibit E. coli O157:H7 growth inhibition in lettuce and carrots | Burt, 2004 |
|                        | and L. monocytogenes growth inhibition in minced pork | Patrignani et al., 2015 |
|                        | control the natural microflora and inhibit Ls. monocytogenes, E. coli in lamb’s lettuce | Burt, 2004 |
| 25. Thymus capitatus    | Ls. monocytogenes growth inhibition in minced beef meat | El Abed et al., 2014 |
| 26. Zingiber officinale | Potential biopreservative of beverages against food spoiling yeasts and bacteria | Sessou et al., 2012 |
gum and chitosan. In addition, Li et al. (2015) developed nanoemulsions that allowed a better aqueous solubility and chemical stability. Eventually, new packaging systems (active packaging) have been studied where essential oils or their main compounds were incorporated into the films. However, until now the research did not provide consistent results (Maisanaba et al., 2016). All these studies showed that the antimicrobial and food preservative potential of natural compounds can be enhanced or maintained by applying physical technologies.

MODE OF ANTIMICROBIAL ACTION OF SPICES

Although the antimicrobial effects of spices and their derivates have been tested against a wide range of microorganisms over the years, their mode of action is still not completely understood. In fact, spices and their essential oils can contain many different bioactive compounds present in variable amounts. Basically, the bioactive constituents of spices can be divided into volatile and non-volatile compounds (Figures 1A,B). The first ones are mainly responsible for the antimicrobial activity of spices. They can be divided in four groups: terpenes, terpenoids, phenylpropenes, and “others” (such as products of degradation; Hyldgaard et al., 2012). Terpenes are evaluated as lesser active antimicrobial compounds amongst the other compounds. For instance, the weak activity of ρ-cymene, one of the main component of thyme, is mainly related to its action as a substitutional membrane impurity. It can affect the melting temperature and the membrane potential, which in turn causes a decrease in cell motility (Hyldgaard et al., 2012). On the other hand, terpenoids, such as the well-studied thymol and carvacrol, exert their antimicrobial activity due to their functional groups (hydroxyl groups and delocalized electrons). For instance, thymol can interact with the membrane both with the polar head-group region of the lipid layer, affecting the permeability, or with the proteins, determining an accumulation of misfolded structures (Hyldgaard et al., 2012; Marchese et al., 2016). These changes can lead to cell leakages that in turn can bring the cell to death (O’Bryan et al., 2015). Once it is inside the cells, thymol can also disrupt important energy-generating processes such as the citrate metabolic pathway and the synthesis of ATP (Hyldgaard et al., 2012; O’Bryan et al., 2015). Carvacrol acts mainly at the level of the membrane as a transmembrane carrier of monovalent cations, exchanging K+ with H+ in the cytoplasm (O’Bryan et al., 2015). Other organic compounds present in spices are phenylpropanes, such as eugenol and cinnamaldehyde. The antimicrobial activity of eugenol is performed mainly at the level of the membranes and proteins, inducing permeabilization and enzyme inactivation. On the contrary cinnamaldehyde, although less powerful than eugenol, can react and cross-link with DNA and proteins other than interact with cell membranes. Eventually, spices possess other degradation compounds originating from unsaturated fatty acids, lactones, terpenes, glycosides, and sulfur- and nitrogen-containing molecules. For instance, the mode of action of AITC, a nitrogen-containing compound, is generally considered as a non-specific inhibition of periplasmic or intracellular targets. In fact, due to its highly electrophile central carbon atom, it can inhibit enzymes and affect proteins by oxidative cleavage of disulfide bonds (Hyldgaard et al., 2012). AITC is the main constituent of mustard essential oil. Clemente et al. (2016) reported that mustard EO induced cell cycle arrest, resulting in bacterial filamentation.

Other than affecting membrane and intracellular stability, Szabo et al. (2010) reported that clove, oregano, lavender, and rosemary essential oils possess quorum sensing inhibitory activity. For instance, molecules such as furanones can be internalized by bacteria, bind to LuxR-type proteins, and destabilize them (Camilli and Bassler, 2006). In this way spices could impact the motility, swarming, and biofilm production of bacteria. Overall, antimicrobial activity of spices cannot be confirmed based only on the action of one compound. The final activity is a synergistic effect of more components.

CONCLUSION

Starting from the food preparation, spices can affect both food spoilage microorganisms (food preservation) and human pathogens (food safety) due to the antimicrobial and antifungal activity of their natural constituents. Spices are provided from natural herbs and plants and generally recognized as safe (GRAS) by the American Food and Drug Administration (FDA). However, the need of high amount of natural compounds represent the main limitation for effective performance against microorganisms. Mostly, their organoleptic characteristics may impact the results of in vitro and in vivo trials. For this reason, combinations of spices or their pure natural compounds, applied with or without additional technologies, represent a promising alternative to avoid this problem. Synergistic effects can lead to a reduction of both natural compounds used and treatment applied. In several cases, additive activities have been also reported. The study of spices, natural compounds, and novel combination technologies can be source of inspiration for developing novel or enhanced molecules acting against spoilage microorganisms.

AUTHOR CONTRIBUTIONS

DG: Data compilation, manuscript writing. DB: Data compilation, table formation. SP: Data compilation, manuscript writing, and formatting. AT: Data compilation, manuscript writing, editing and formatting, and final approval.

ACKNOWLEDGMENTS

We thank Prof. V. Craig Jordan (Father of Tamoxifen) for providing the facility to revise the manuscript. This research was supported by a grant from the Ministry of Education, Science and Technological Development of Serbia (Project No. 173029).
Divya, K., Ramalakshmi, K., Murthy, P. S., and Mohan Rao, J. L. (2014). Volatile oils from Ferula asafoetida varieties and their antimicrobial activity. IWT Food Sci. Technol. 59, 774–779. doi: 10.1016/j.iwtfst.2014.07.013

Doherty, V. E., Olaniyan, O. O., and Kanife, U. C. (2010). Antimicrobial activities of Aframomum melegueta (Alligator pepper). Int. J. Biol. 2, 126–131. doi: 10.5539/jib.v2n2p126

Droyem, J. P., Thchuenguem, R. T., Kuate, J. R., Teke, G. N., Kecha, F. A., and Kuate, V. (2014). In vitro and in vivo antifungal activities of selected Cameroonan dietary spices. BMC Complement. Altern. Med. 14:58. doi: 10.1186/1472-6882-14-58

El, S. N., and Karakaya, S. (2009). Olive tree (Olea europaea) leaves: potential beneficial effects on human health. Nutr. Rev. 67, 632–638. doi:10.1111/j.1753-4887.2009.00248.x

El Abed, N., Kaabi, B., Smaali, I. M., Chabbouh, M., Habibi, K., Marzouki, M. N., et al. (2011). Chemical composition, antioxidant and antimicrobial activities of Thymus capitata essential oil with its preservative effect against Listeria monocytogenes inoculated in minced beef meat. J. Evid. Based Complement. Altern. Med. 2014:152487. doi: 10.1155/2014/152487

Elhassan, I. A., Elamin, E. E., Mohamed, S., and Ayoub, H., (2010). Chemical composition of essential oil in dried fruits of Xylopia aethiopica from Sudan. J. Med. Aromatic Plants 1, 24–28.

Elumalai, A., and Eswareniah, M. C. (2011). A pharmacological review on Garcinia indica Choisy. Int. J. Univer. Pharm. Life Sci. 1, 508–206.

Eng-Chong, T., Yeang-Kee, L., Chin-Fei, C., Choon-Han, H., Sher-Ming, W., Thio Li-Ping, C., et al. (2012). Bosoenhergia rotundata: from ethnomedicine to drug discovery. J. Evid. Based Complement. Altern. Med. 2012:473637. doi: 10.1155/2012/473637

Emazeli, A., Masoudi, S., Masnabadi, N., and Rustaiyan, A. H. (2010). Chemical constituents of the essential oil of Sanguisorba minor Scop. leaves, from Iran. J. Med. Plants 9, 67–70.

Eyob, S., Martinsen, B. K., Tsegaye, A., Appelgren, M., and Skrede, G. (2008). Multitargeting by turmeric, the golden spice: from kitchen to clinic. J. Med. Plants 8, 774–779. doi:10.1016/j.lwt.2014.07.013

Ghosh, A. K., Banerjee, S., Mullick, H. I., and Banerjee, J. (2011). Zingiber officinale: a natural gold. Int. J. Pharm. Bio. Sci. 2, 283–294.

Gong, Y. W., Huang, Y. F., Zhou, L. G., and Jianf, W. (2009). Chemical composition and antifungal activity of the fruit oil of Zanthoxylum bungeanum Maxim. (Rutaceae) from China. J. Ess. Oil Res. 21, 174–178. doi:10.1177/1041290509337014

Gorai, D., Jash, K. S., Singh, R. K., and Gangopadhyay, A. (2014). Chemical and pharmacological aspects of Limoniphila aromatica (Sphorulariaeaceae): an overview. Am. J. Phytomed. Clin. Ther. 2, 348–356.

Gulfarz, M., Sadiq, A., Tariq, H., Imran, M., Qureshiand, R., and Zeenat, A. (2011). Phytochemical analysis and antimicrobial activity of Erucas sativa seed. Pak. J. Bot. 43, 1351–1359.

Gupta, A. D., Bansal, V. K., Babu, V., and Maithil, N. (2013). Chemistry, antioxidant and antimicrobial potential of nutmeg (Myristica fragrans Houtt) J. Genet. Eng. Biotechnol. 11, 25–31. doi:10.1016/j.jgeb.2012.12.001

Gupta, S. C., Sung, B., Kim, J. H., Prasad, S., Li, S., and Aggarwal, B. B. (2013a). Antioxidant and antimicrobial activity of plant essential oils using food model media: efficacy, synergistic potential and interaction with food components. Food Microbiol. 26, 142–150. doi:10.1016/j.fm.2008.10.008

Haidaria, F., Keshavzarb, S. A., Shahia, M. M., Mahboob, S. A., and Rashidid, M. R. (2011). Effects of parsley (Petroselinum crispum) and its flavonol constituents, kaempferol and quercetin, on serum uric acid levels, biomarkers of oxidative stress and liver xanthine oxidoreductase activity in oxonate-induced hyperuricemic rats. Iran. J. Pharm. Res. 9, 811–819.

Hamad, M. N. (2012). Isolation of rutin from Rutaceae (Rutaceae) cultivated in Iraq by precipitation and fractional solubilisation. Pharmacene Globale 3, 1–3.

Handral, H. K., Pandith, A., and Shruthi, S. D. (2012). A review on Murraya koenigii: multipotential medicinal plant. Asian J. Pharm. Clin. Res. 5, 5–14.

Hayam, I., Ibrahim, Ferial, M., and Abu, S. (2013). Effect of adding lemongrass and lime peel extracts on chicken patties quality. J. Appl. Sci. Res. 9, 5003–5047.

Hayouni, E. A., Chraief, I., Abedrabba, M., Bouix, M., Leveau, J. Y., Mohammed, H., et al. (2008). Tunisian Salvia officinalis L. and Schinus molle L. essential oils: their chemical compositions and their preservative effects against Salmonella inoculated in minced beef meat. Int. J. Food Microbiol. 125, 242–251. doi: 10.1016/j.ifm.2008.04.005

Hemati, A., Aazarinia, M., and Angaji, S. A. (2010). Medicinal effects of Heracleum persicum (Golpar). Middle East J. Sci. Res. 5, 17–176.

Hernández-Hernández, E., Regalado-González, C., Vázquez-Landaverde, P., Guerrero-Lagarreta, I., and García-Almendrás, B. E. (2014). Microencapsulation, chemical characterization, and antimicrobial activity of Mexican (Lippia graveolens H.B.K.) and European (Origanum vulgare L.) oregano essential oils. Sci. World J. 2014:641814. doi: 10.1155/2014/641814

Hoque, M. M., Rattila, S., Shishir, M. A., Bari, M. L., Inatsu, Y., and Kawamoto, S. (2011). Antibacterial activity of ethanol extract of betel leaf (Piper betle L.) against some food borne pathogens. Bangladesh J. Microbiol. 28, 58–63. doi:10.3329/bjm.v28i2.11817

Hernández-Ochoa, L., Aguirre-Prieto, Y. B., Nevárez-Moorellón, G. V., Gutierrez-Mendez, N., and Salas-Mu-oz, E. (2014). Use of essential oils and extracts from spices in meat preservation. J. Food Sci. Technol. 51, 957–963. doi:10.1007/s13197-011-0598-3

Hosuna, A. B., Trigui, M., Mansour, R. B., Jarraya, R. M., Damak, M., and Jaoua, S. (2011). Chemical composition, cytotoxicity effect and antimicrobial activity of Ceratonia silique essential oil with preservative effects against Listeria inoculated in minced beef meat. Int. J. Food Microbiol. 148, 66–72. doi: 10.1016/j.ifm.2011.04.028

Hu, Y. M., Ye, W. C., Yin, Z. Q., and Zhao, S. X. (2007). Chemical constituents from flos Sesamum indicum L. Yao Xue Xue Bao 42, 286–291.

Hyldgaard, M., Mygind, T., and Meyer, R. L. (2012). Essential oils in food preservation: mode of action, synergies, and interactions with food matrix components. Front. Microbiol. 3:12. doi: 10.3389/fmicb.2012.00112

Hymete, A., Rohlff, I., and Iversen, T. H. (2006). Essential oil from seeds and husks of Aframomum corrumma from Ethiopia. Flavour Frag. J. 21, 642–644. doi:10.1002/ffj.1634

Hymete, A., Rohlff, I., and Iversen, T. H. (2006). Essential oil from seeds and husks of Aframomum corrumma from Ethiopia. Flavour Frag. J. 21, 642–644. doi:10.1002/ffj.1634
Shiva Rani, S. K., Neeti, S., and Udayasree (2013). Antimicrobial activity of black pepper (Piper nigrum L.). Glob. J. Pharmacol. 7, 87–90. doi: 10.5829/idosi.gjp.2013.7.1.1104

Simons, V., Morrissy, J. P., Latijnhouwers, M., Csukai, M., Cleaver, A., Yarrow, C., et al. (2006). Dual effects of plant steroidal alkaloids on Saccharomyces cerevisiae. Antimicrob. Agents Chemother. 50, 2732–2740. doi: 10.1128 AAC.20089-06

Singh, G., Maurya, S., DeLampasona, M. P., and Catalán, C. A. N. (2007). A comparison of chemical, antioxidant and antimicrobial studies of cinnamon leaf and bark volatile oils, oleoresins and their constituents. Food Chem. Toxicol. 45, 1650–1661. doi: 10.1016/j.jct.2007.02.031

Siroli, L., Patrignani, F., Montanari, C., Tabanelli, G., Bargossi, E., Gardini, F., et al. (2014b). Characterization of oregano (Origanum vulgare) essential oil and definition of its antimicrobial activity against Listeria monocytogenes and Escherichia coli in vitro system and on foodstuff surfaces. Afr. J. Microbiol. Res. 8, 2746–2753. doi: 10.5897/AJMR2014.6677

Siroli, L., Patrignani, F., Serrazanetti, D. L., Tabanelli, G., Montanari, C., Tappi, S., et al. (2014a). Efficacy of natural antimicrobials to prolong the shelf-life of minimally processed apples packaged in modified atmosphere. Food Control 46, 403–411. doi: 10.1016/j.foodcont.2014.05.049

Srinagar, M. M., and Nemet, N. T. (2009). Antimicrobial effect of spices and herbs essential oils. Acta Period. Technol. 40, 195–209. doi: 10.2298/APT09 4019SS

Spadaro, F., Costa, R., Circosta, C., and Occhiuto, F. (2012). Volatile composition and biological activity of key lime Citrus aurantiifolia essential oil. Nat. Prod. Commun. 7, 1523–1526.

Srivivasan, K. (2014). Antioxidant potential of spices and their active constituents. Crit. Rev. Food Sci. Nutr. 54, 352–372. doi: 10.1080/01608398.2011.585525

Stoilova, I., Krestanov, A., Stoyanova, A., Denev, P., and Gargova, S. (2007). Antimicrobial activity of a ginger extract (Zingiber officinale). Food Chem. 102, 764–770. doi: 10.1016/j.foodchem.2006.06.023

Suleyman, K., Hasimi, N., Tolan, V., Kilinc, E., and Karatas, H. (2010). Chemical composition, antimicrobial and antioxidant activities of hyssop (Hyssopus officinalis L.) essential oil. No-tulea Botanicae Horti Agrobotanici Cluj-Napoca 38, 99–103. doi: 10.15835/nbha3834788

Sultana, S., Ripa, F. A., and Hamid, K. (2010). Comparative antioxidant activity study of some commonly used spices in Bangladesh. Pak. J. Biol. Sci. 13, 340–343. doi: 10.3923/pjbs.2010.340.343

Sung, B., Prasad, S., Yadav, V. R., and Aggarwal, B. B. (2012). Cancer cell signaling pathways targeted by spice-derived nutraceuticals. Nutr. Cancer 64, 173–197. doi: 10.1080/01635581.2012.630551

Szabo, M. A., Varga, G. Z., Hohmann, J., Schel, Z., Szegedi, E., Amalar, L., et al. (2010). Inhibition of quorum-sensing signals by essential oils. Phytother. Res. 24, 782–786. doi: 10.1002/ptr.3010

Tabanelli, G., Montanari, C., Patrignani, F., Siroli, L., Lanciotti, R., and Gardini, F. (2014). Modeling with the logistic regression of the growth/no growth interface of Saccharomyces cerevisiae in relation to 2 antimicrobial terpenes (Citral and Linalool), pH, and aw. J. Food Sci. 79, M391–M398. doi: 10.1111/1750 3841.12369

Tabassum, N., and Vidsagar, G. M. (2013). Antifungal investigations on plant essential oils. a review. Int. J. Pharm. Pharm. Sci. 5, 340–343. doi: 10.3923/ijps.2010.340.343

Tajkarimi, M. M., Ibrahim, S. A., and Cliver, D. O. (2010). Antimicrobial and spice compounds in food. Food Control 21, 1199–1218. doi: 10.1016/j.foodcont.2010.02.003

Tejeswini, M. G., Sowmya, H. V., Swarnalatha, S. P., and Negi, P. S. (2014). Antifungal activity of essential oils and their combinations in in vitro and in vivo conditions. Arch. Phytopathol. Plant Protect. 47, 564–570. doi: 10.3923/ajpb.2010.32350.2013.814235

Torabbeigi, M., and Azar, P. A. (2013). Analysis of essential oil compositions of Lavandula angustifolia by HS-SPME and MAHS–SPME Followed by GC and GC–MS. Acta Chromatogr. 25, 1–9. doi: 10.1556/Achrom.25.2013.3.12

Tyagi, A. K., Bukvicki, D., Gottardi, T., Tabanelli, G., Montanari, C., Malik, A., et al. (2014b). Eucalyptus essential oil as a natural food preservative: in vivo and in vitro anti-yeast potential. Biomed. Res. Int. 2014:969143. doi: 10.1155/ 2014/969143

Tyagi, A. K., Gottardi, T., Malik, A., and Guerzoni, M. E. (2013). Anti-yeast activity of mentha oil and vapours through in vitro and in vivo real
Tyagi, A. K., Gottardi, D., Malik, A., and Guerzoni, M. E. (2014a). Chemical composition, in vitro anti-yeast activity and fruit juice preservation potential of lemon grass oil. *LWT Food Sci. Technol.* 57, 731–737. doi:10.1016/j.lwt.2014.02.004

Tyagi, A. K., and Malik, A. (2010a). Antimicrobial action of essential oil vapours and negative air ions against *Pseudomonas fluorescens*. *Int. J. Food Microbiol.* 143, 205–210. doi:10.1016/j.ijfoodmicro.2010.08.023

Tyagi, A. K., and Malik, A. (2010b). Liquid and vapour-phase antifungal activities of selected essential oils against *Candida albicans*: microscopic observations and chemical characterization of *Cymbopogon citratus*. *BMC Complement. Altern. Med.* 10:65. doi:10.1186/1472-6882-10-65

Tyagi, A. K., and Malik, A. (2010c). In situ SEM, TEM and AFM studies of the antimicrobial activity of lemon grass oil in liquid and vapour phase against *Candida albicans*. *Micron* 41, 797–805. doi:10.1016/j.micron.2010.05.007

Tyagi, A. K., and Malik, A. (2011). Antimicrobial potential and chemical composition of *Mentha piperita* oil in liquid and vapour phase against food spoiling microorganisms. *Food Control* 22, 1707–1714. doi:10.1016/j.foodcont.2011.04.002

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

Umar, M. L, Asmawi, M. Z. B., Sadikun, A., Altaf, R., and Iqbal, M. A. (2011). Phytochemistry and medicinal properties of *Kaempferia galanga* L. (Zingiberaceae) extracts. *Afr. J. Pharm. Pharmacol.* 5, 1638–1647. doi:10.5897/AJPP11.388

Unlu, M., Ergene, E., Unlu, G. V., Zeytinoglu, H. S., and Vural, N. (2010). Composition, antimicrobial activity and in vitro cytotoxicity of essential oil from *Cinnamomum zeylanicum* blume (lauraceae). *Food Chem. Toxicol.* 48, 3274–3280. doi:10.1016/j.fct.2010.09.001

Upadhyay, R. K., Ahmad, S., Jaiswal, G., Dwivedi, P., and Tripathi, R. (2008). Antimicrobial effects of *Cleome viscosa* and *Trigonella foenum graecum* seed extracts. *J. Cell Tissue Res.* 8, 1355–1360.

Vazirian, M., Kashani, S. T., Ardekani, M. R. S., Khanavi, M., Jamalifar, H., Reza, M., et al. (2012). Antimicrobial activity of lemongrass (*Cymbopogon citratus* (DC) Stapf) essential oil against food-borne pathogens added to cream-filled cakes and pastries. *J. Ess. Oil Res.* 24, 579–582. doi:10.1080/10412905.2012.729920

Vryy Wouaatsa, N. A., Misra, L., and Venkatesh Kumar, R. (2014). Antibacterial activity of essential oils of edible spices, *Ocimum canum* and *Xylopia aethiopica*. *J. Food Sci.* 79, M972–M977. doi:10.1111/1750-3841.12457

Weerakkyody, N. S., Caffin, N., Turner, M. S., and Dykes, G. A. (2010). In vitro antimicrobial activity of less-utilized spice and herb extracts against selected food-borne bacteria. *Food Control* 21, 1408–1414. doi:10.1016/j.foodcont.2010.04.014

Woguem, V., Maggi, F., Fogang, H. P., Tapondjoua, L. A., Womeni, H. M., Luana, Q., et al. (2013). Antioxidant, antiproliferative and antimicrobial activities of the volatile oil from the wild pepper *Piper capense* used in Cameroon as a culinary spice. *Nat. Prod. Comm.* 8, 1791–1796.

Xu, S., Yan, F., Ni, Z., Chen, Q., Zhang, H., and Zheng, X. (2014). In vitro and in vivo control of *Alternaria alternata* in cherry tomato by essential oil from *Laurus nobilis* of Chinese origin. *J. Sci. Food Agric.* 94, 1403–1408. doi:10.1002/jsfa.6428

Yadav, A. S., and Singh, R. (2004). Natural preservatives in poultry meat. *Indian J. Nat. Prod. Resour.* 3, 300–303.

Zheng, C. J., Li, L., Ma, W. H., Han, T., and Qin, L. P. (2011). Chemical constituents and bioactivities of the liposoluble fraction from different medicinal parts of *Crocus sativus*. *Pharm. Biol.* 49, 756–763. doi:10.3109/135880209.2010.547206

Zhu, R. X., Zhong, K., Zeng, W. C., He, X. Y., Gu, X. Q., Zhao, Z. F., et al. (2011). Essential oil composition and antibacterial activity of *Zanthoxylum bungeanum*. *Afr. J. Microbiol. Res.* 5, 4631–4637. doi:10.5897/AJMR11.772

**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.

**Copyright © 2016 Gottardi, Bukuvički, Prasad and Tyagi. 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.**