



HAL
open science

Plant antimicrobial polyphenols as potential natural food preservatives

Lynda Bouarab Chibane, Pascal Degraeve, Hicham Ferhout, Jalloul Bouajila,
Nadia Oulahal

► To cite this version:

Lynda Bouarab Chibane, Pascal Degraeve, Hicham Ferhout, Jalloul Bouajila, Nadia Oulahal. Plant antimicrobial polyphenols as potential natural food preservatives. *Journal of the Science of Food and Agriculture*, 2019, 99 (4), pp.1457-1474. 10.1002/jsfa.9357 . hal-02057251

HAL Id: hal-02057251

<https://hal.science/hal-02057251>

Submitted on 5 Mar 2019

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.




Open Archive Toulouse Archive Ouverte

OATAO is an open access repository that collects the work of Toulouse researchers and makes it freely available over the web where possible

This is an author's version published in: <http://oatao.univ-toulouse.fr/23195>

Official URL : <https://doi.org/10.1002/jsfa.9357>

To cite this version :

Bouarab Chibane, Lynda and Degraeve, Pascal and Ferhout, Hicham and Bouajila, Jalloul  and Oulahal, Nadia *Plant antimicrobial polyphenols as potential natural food preservatives*. (2018) *Journal of the Science of Food and Agriculture*, 99 (4). 1457-1474.
ISSN 0022-5142

Any correspondence concerning this service should be sent to the repository administrator: tech-oatao@listes-diff.inp-toulouse.fr

Plant antimicrobial polyphenols as potential natural food preservatives

Lynda Bouarab Chibane,^a Pascal Degraeve,^a Hicham Ferhout,^b
Jalloul Bouajila^c and Nadia Oulahal^{a*} 

Abstract

BACKGROUND: The growing demand for natural food preservatives in the last decade has promoted investigations on their application for preserving perishable foods. In this context, the present review is focused on discussing the prospective application of plant extracts containing phenolics or isolated plant phenolics as natural antimicrobials in foods. Plant essential oils are outside the scope of this review since utilization of their antimicrobial activity for food preservation has been extensively reviewed.

RESULTS: Although the exact antimicrobial mechanisms of action of phenolic compounds are not yet fully understood, it is commonly acknowledged that they have diverse sites of action at the cellular level. Antimicrobial phenolics can be added directly to the formulation of perishable food products or incorporated into food-contact materials to release them in the immediate zone of perishable foods. Edible coatings or active food packaging materials can thus be used as carriers of plant bioactive compounds.

CONCLUSION: These materials could be an interesting delivery system to improve the stability of phenolics in foods and to improve the shelf life of perishable foods. This review will thus provide an overview of current knowledge of the antimicrobial activity of phenolic-rich plant extracts and of the promises and limits of their exploitation for the preservation of perishable foods.

© 2018 Society of Chemical Industry

Keywords: plant extracts; phenolic compounds; antimicrobial activity; food preservation; edible coatings

INTRODUCTION

The use of natural antimicrobials for food preservation is a trend that is followed by both consumers and food manufacturers. In the future, their use is expected to increase gradually because of the rising demand for minimally processed products, preferably those containing natural additives.

Despite considerable efforts to improve production technologies, distribution, hygiene standards, and consumer education, spoilage and foodborne pathogenic microorganisms still lead to huge economic losses and unacceptable human costs. Due to the increase in the consumption of fresh, minimally processed, and ready-to-eat foods, new ecological routes for microbial growth have emerged. To ensure the microbial safety of their food, consumers demand 'healthier' and more environmentally friendly food production systems, which promote the development of innovative biopreservation concepts based on the use of natural antimicrobial agents rather than synthetic preservatives.

Such concerns and the growing demand for organic foods are driving a growing interest in natural antimicrobials, which exhibit an effective antagonistic effect against a wide range of unwanted microorganisms in foods. The present knowledge shows that the growth of pathogenic and spoilage microorganisms may be strongly reduced or inhibited by several plant extracts. Their effective antimicrobial activities make them potentially an interesting alternative to synthetic preservatives. Antimicrobial plant extracts or molecules, such as an extract of moso bamboo (Takeguard™)

launched by Takex Labo (Osaka, Japan) or a mixture of different natural antimicrobial extracts (Biovia™ YM10) including green tea extract launched by Danisco DuPont, have been proposed as alternatives to chemical ones. Thousands of antimicrobial plant molecules have been listed in the botanical literature and represent a renewable source of bioactive constituents. Natural antimicrobials traditionally used and recorded by individuals are a small part of the preservatives available in nature. Currently, there is a need to expand the list of natural antimicrobial molecules that could be used as food preservatives.

Most of the natural alternatives to synthetic food preservatives investigated in recent studies are plant extracts in raw or purified form, namely, essential oils or pure compounds, most of which were used by our ancestors. They have become the center of interest for *in situ* application in food products.¹ In this context,

* Correspondence to: N Oulahal, BioDyMIA, Département de Génie Biologique IUT Lyon 1, technopole Alimentec, rue Henri de Boissieu, F-01000 Bourg en Bresse, France. E-mail: nadia.oulahal@univ-lyon1.fr

^a BioDyMIA (Bioingénierie et Dynamique Microbienne aux Interfaces Alimentaires), EMA 3733, Univ Lyon, Université Claude Bernard Lyon 1, Isara Lyon, Bourg en Bresse, France

^b Nat'ex Biotech, Toulouse, France

^c Faculté de Pharmacie de Toulouse, Laboratoire de Génie Chimique, UMR CNRS 5503, Université Paul Sabatier, Toulouse, France

essential oils are the plant extracts that have been the most studied for their antimicrobial activity. However, in addition to their higher cost than other plant extracts (due to their lower extractability and yield), essential oils contain volatile compounds (frequently unpleasant or generating off-odors) and have low water solubility. These drawbacks often limit their use for food preservation. Since applications of essential oils for improving food safety have been widely reviewed by Burt² and more recently by Hyldgaard *et al.*,³ essential oils are outside the scope of this review, which will instead be focused on other plant extracts.

Plant extracts play an important role because of their nutritional, visual (color), and taste properties; polyphenols are thus considered relevant due to their qualities.⁴ Most of the applications of phenolic-rich plant extracts for food safety purposes are related to their antioxidant activity, including the prominent example of rosemary extract,⁵ which has food additive status in the European Union (E 392). Antioxidant rosemary extract contains more than 900 g kg⁻¹ of carnosic acid and carnosol, both of which are phenolics.

In addition to these antioxidant properties, polyphenols have also been shown to extend the shelf life of some food products through their antimicrobial activities, and they may also act as inhibitors of pathogenic microorganisms.⁶

This review will thus help the reader to identify (i) phenolic-rich plant extracts with potential as antimicrobials, (ii) their mechanism of action, (iii) the factors known to affect their *in situ* antimicrobial activity in real food systems, and (iv) most of their potential applications for perishable food preservation reported up to now.

NATURAL EXTRACTS/MOLECULES FOR FOOD PRESERVATION

Edible plants: a potential source of antimicrobial molecules

Controlling microbial growth in food products has always been a major concern for the different stakeholders in the agri-food sector. A double challenge must be considered: ensuring both food safety and food waste reduction. In fact, microbes causing infectious diseases are frequently the cause of morbidity and mortality

across the world. In addition, microbial spoilage induces the loss of approximately a quarter of the world's food supply, and more than 40% of food damage occurs at the retail and consumer levels in developed countries.⁷ This context has induced a rise in biocide and antibiotic application in order to guarantee efficient control of the microbial contamination of foods.

The emergence and spread of antibiotic resistance among human pathogenic microorganisms are a critical challenge. Indeed, the appearance of resistance or even multiresistance in a large bacterial community can be induced by the routine use of antibiotics.⁸ In addition to this phenomenon of antibiotic resistance, the presence of antimicrobial agent residues in the environment has attracted much attention from modern consumers. Thus, the search for natural antimicrobials that are effective against both pathogenic and spoilage microorganisms is crucial.

Natural preservatives are considered healthier and to have an added value arising from their bioactivity and nutritional value. Therefore, an increasing number of food companies have made an effort to meet the increasing consumer demand for natural food preservatives. However, a soft transition from chemical additives to natural alternatives is expected, particularly because of economic and antimicrobial efficacy issues that still have to be solved.¹

Plant-derived antimicrobials are promising in this context. Indeed, plant extracts are generally considered edible based on their traditional human consumption. In addition, plant secondary metabolites (PSMs) account for the greatest diversity of structures (e.g. there are more than 12 000 known alkaloids, more than 10 000 phenolic compounds and over 25 000 different terpenoids). Different antimicrobial polyphenol subgroups, their chemical structures and examples are presented in Fig. 1.

Antimicrobial PSMs were thus proposed as potential alternatives to synthetic preservatives. Nevertheless, plant-derived antimicrobials have not been frequently applied until now. To expand the use of plant extracts as natural preservatives, their bioactive compounds could be extracted and purified by developing economic processes preserving their activities.

Typically, extraction of phenolic compounds as a mixture and their purification are simple to perform. The edible plant-derived compounds remain the most favored for food use to limit concern

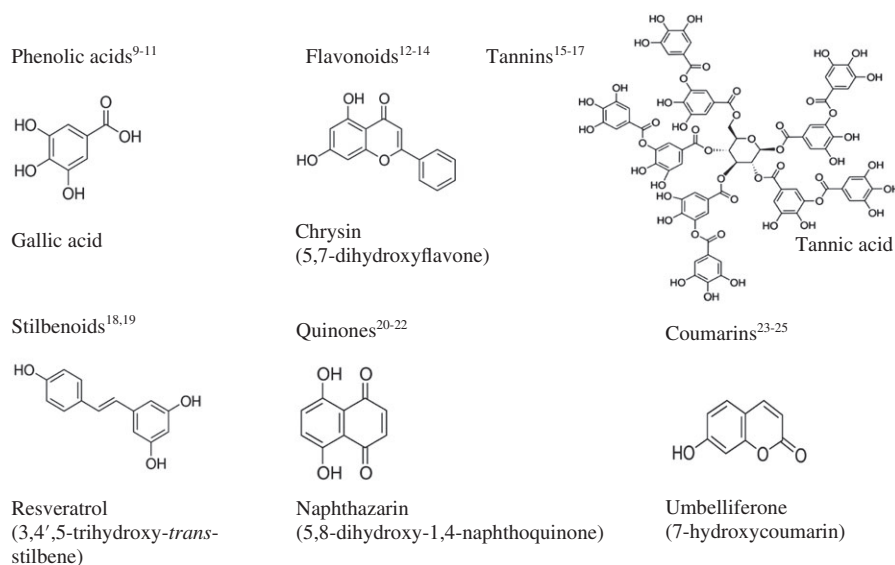


Figure 1. Major groups of plant-derived antimicrobial phenolics, chemical structures and examples. Phenolic acids,⁹⁻¹¹ flavonoids,¹²⁻¹⁴ tannins,¹⁵⁻¹⁷ stilbenoids,^{18,19} quinones²⁰⁻²² and coumarins.²³⁻²⁵

regarding toxicity. Therefore, several recent studies have explored these plants as a potential source of antimicrobial molecules. The *in vitro* antimicrobial activity of the most studied edible plants byproducts in the past decade is described in Table 1.

Polyphenols: a diversity of antimicrobial mechanisms of action

The OH groups of phenolic compounds interact with the cell membrane of bacteria by hydrogen bonding. Importantly, the presence of OH functional groups is relevant to the antibacterial activity of many phenolics.^{57–60} Indeed, the interaction of phytochemicals with bacterial cell membranes usually causes either the disruption of the membrane structure, which induces loss of cellular content,^{58,61} or the delocalization of electrons (because of the double bonds of the aromatic nucleus), which results in depolarization of bacteria (acting as proton exchangers) and thus affects the proton motive force, reducing the pH gradient across the membrane and the level of the ATP pool.⁶⁰ This series of mechanisms initiated by the active hydroxyl groups of phytochemicals such as phenolics can lead to cell death. Furthermore, the relative position of the OH group on the phenolic nucleus has been reported to influence the antibacterial efficacy of phenolic compounds.⁶²

The presence of alkyl groups in the aromatic nucleus generates phenoxyl radicals⁶³ reported to enhance the antibacterial efficacy of phenolics and alter their distribution ratio between aqueous and non-aqueous phases, including bacterial phases.⁶⁴ The presence of an acetate moiety in the molecular structure appeared to increase the activity of parent phenolic compounds by either the alcohol groups as protein denaturing agents⁶⁴ or by an increase in their electronegativity due to the aldehyde groups promoting electron transfer and reactions with membrane proteins.⁶⁵ The galloyl moiety has been reported to induce important damage to the membrane structure, thereby enhancing the antibacterial activity of epigallocatechin gallate against Gram-positive bacteria.⁶⁶ In addition to their chemical composition and structure, the lipophilic properties of phytochemicals are also involved in their antibacterial activity.⁶³

The antimicrobial activity of many phenolics has been observed to increase with the elevation of their lipophilic character; this may be directly related to their potential interactions with the cell membrane.⁶⁶ The ability to penetrate the cell membrane and interact with cell compounds induces irreversible damage to the cell membrane and coagulation of the cell content, affecting both membrane and intracellular enzymes. Hydrogen-bonding descriptors (H-bond donors, H-bond acceptors), polar surface area, log *P* (octanol/water partition coefficient) and HOMO (highest occupied molecular orbital) and LUMO (lowest unoccupied molecular orbital) energy levels are the physicochemical parameters involved in the capacity of bioactive molecules to permeate through lipid membranes.^{67,68} Van der Waals bonding can be established when the electron bonding energy of phenolics (acting as hydrogen bond donors) is higher than that of membrane lipids. A high number of hydrogen bond donors leads to higher interactions with the membrane of bacteria. Furthermore, molecules with a polar surface area of greater than 140 Å squared (higher than acyl chains) tend to interact strongly with the choline head groups of membrane phospholipids.⁶⁹ Strong interactions with the Caco-2 cell model membrane have been observed for molecules with log *P* values higher than 0 and less than 3,⁶⁸ allowing them to get closer to membrane surfaces and interact with them; however, such data regarding bacterial membranes are lacking. Attraction between two different molecules can be induced by the interaction

between their HOMO and LUMO. The difference in the HOMO and LUMO energy levels between phenolics and lipids constitutes a key element for bacterial membrane and phenol interactions.

The main antimicrobial mechanisms of action of polyphenols cited in this review are summarized in Fig. 2.

Not all information on the mechanisms of the antimicrobial action of phenolics has been acquired yet. However, these components are considered to have many sites of action at the cellular level.⁷⁰ There are at least three mechanisms on which several authors agree: (i) modification of the permeability of cell membranes, formation of cytoplasmic granules and rupture of the cytoplasmic membrane; (ii) changes in various intracellular functions induced by hydrogen bonding of the phenolic compounds to enzymes through their OH groups; and (iii) modification of fungal morphology (cell wall rigidity and integrity losses) induced by different interactions with cell membranes.⁷¹

In general, Gram-negative bacteria are more resistant to PSMs, including phenolics, than Gram-positive bacteria.⁷² This difference is likely because Gram-negative bacteria possess a cell wall linked to an outer complex membrane,⁷³ namely, the lipopolysaccharide envelope, which slows down the passage of phytochemicals.^{74,75} Nevertheless, the appearance of lipopolysaccharides released from the outer membrane provides evidence that some polyphenols may also affect the outer membrane of Gram-negative bacteria.^{76–78}

Additional impacts were reported when Gram-positive bacteria and fungi were considered. The first one is the modification of intracellular pH (due to variations in the flow of ions such as H⁺ and K⁺ influencing the proton motive force), and the second one is the blocking of energy production (interference with the energy (ATP)-generating system).⁷⁹

Condensed phenylpropanoids – tannins – may induce damage at the cell membrane level and even inactivate metabolism by binding to enzymes,^{80,81} while phenolic acids have been shown to disrupt membrane integrity, as they cause consequent leakage of essential intracellular constituents.¹⁰

Flavonoids are considered able to promote complex formation by linking with soluble proteins located outside the cells and within the cell walls of bacteria.^{82,83} Quercetin was reported to have a significant effect on the bacterial membrane by increasing the membrane permeability and disturbing its potential.⁸⁴ Investigations on the membrane action of several flavonoids ((–)-epigallocatechin gallate,⁷¹ (–)-epicatechin gallate and 3-*O*-octanoyl-(+)-catechin,⁸⁵ as well as 2,4,2'-trihydroxy-5'-methylchalcone⁸⁶) showed that these compounds induce a reduction in membrane fluidity.

Furthermore, some flavonoids may act by inhibiting both energy metabolism and DNA synthesis, as observed by Haraguchi *et al.*,⁸⁷ and affect protein and RNA syntheses to a lesser extent. In addition to their versatile activities, catechins exert antibacterial effects via DNA gyrase inhibition.⁸⁸

Other flavonoids, such as apigenin, have been proven to have an inhibitory effect on the activity of DNA gyrase and hydroxyacyl-acyl carrier protein dehydratase.^{83,89}

Naphthoquinones (e.g. plumbagin) were found to inhibit potential efflux pumps. Interestingly, they have been shown to have a significant antibacterial effect against Gram-negative bacteria, whose resistance to most natural antimicrobial products is related to efflux pumps,⁹⁰ while coumarins have been reported to cause a reduction in cell respiration.¹⁶

Recent advances in multiparameter flow cytometry offer the opportunity to obtain high-speed information on the

Table 1. *In vitro* antimicrobial effect of aqueous extracts from the most studied edible plants byproducts in the past decade (from 2007 to 2017)

Byproducts	Major component	Target organisms	References
Coffee pulp extract	Polyphenols such as flavan-3-ols, hydroxycinnamic acids, flavonols, and anthocyanidins	<i>Pseudomonas fluorescens</i> , <i>Staphylococcus aureus</i> , <i>Aspergillus flavus</i>	26
Spent coffee extract	Flavan-3-ols, hydroxycinnamic acids, flavonols, and anthocyanidins	<i>Staphylococcus aureus</i> , <i>Listeria monocytogenes</i> , <i>Bacillus subtilis</i> , <i>Candida albicans</i>	27
Green tea waste	Tannins	<i>Staphylococcus aureus</i> , <i>Escherichia coli</i> , <i>Listeria monocytogenes</i> , <i>Bacillus coagulans</i> , <i>Shigella flexneri</i>	28
Green, white and black tea extracts	Tannins	<i>Salmonella typhimurium</i> , <i>Listeria monocytogenes</i>	29
Olive pomace	Phenolic compounds including oleocanthal, deoxyloganic acid lauryl ester	<i>Escherichia coli</i> O157:H7, <i>Salmonella enteritidis</i> , <i>Listeria monocytogenes</i> , and <i>Staphylococcus aureus</i>	30
Olive leaf extract	Phenolics and flavonoids	<i>Listeria monocytogenes</i> , <i>Escherichia coli</i> O157:H7, <i>Salmonella enteritidis</i> , <i>Candida albicans</i>	31,32
Pomegranate fruit peel extract	Phenolics and flavonoids	<i>Salmonella</i> spp., <i>Listeria monocytogenes</i> , <i>Staphylococcus aureus</i> , <i>Escherichia coli</i> , <i>Yersinia enterocolitica</i> , and <i>Pseudomonas fluorescens</i>	33,34,35,36,37,38,39
Pomegranate aril and peel extracts	Phenolics and flavonoids	<i>Pseudomonas stutzeri</i>	40
Winery products	Phenolic acids, flavonoids, stilbenes	Gram-negative bacteria, Gram-positive bacteria, and fungi <i>Staphylococcus aureus</i> , <i>Escherichia coli</i> <i>Bacillus cereus</i> , <i>Campylobacter jejuni</i> , <i>Escherichia coli</i> , <i>Listeria monocytogenes</i> , <i>Salmonella enterica</i> , <i>Staphylococcus aureus</i> , <i>Yersinia enterocolitica</i>	41
Grape pomace	Phenolic acids, flavonoids, stilbenes	<i>Staphylococcus aureus</i> , <i>Salmonella</i> , <i>Enterococci</i> , total aerobic mesophilic and psychrotrophic bacteria <i>Escherichia coli</i> , <i>Salmonella enteritidis</i> , <i>Salmonella typhimurium</i> , <i>Staphylococcus aureus</i> , and <i>Yersinia enterocolitica</i> yeasts, and molds <i>Campylobacter jejuni</i> <i>Campylobacter jejuni</i> <i>Pseudomonas</i> spp. <i>Listeria monocytogenes</i>	42 43 44 45
Grape fruit seed extract	Flavonols, phenolic acids, catechins, proanthocyanidins and anthocyanins	Total bacterial count, coliforms, and <i>Escherichia coli</i>	46 47 48
Mango seed kernel extract	Phenolic compounds, saturated fatty acids, monounsaturated oleic acid, tocopherols, squalene, and different sterol fractions		49
Myrtle berries seeds extract	Phenolic acids and flavonoids	<i>Escherichia coli</i> , <i>Staphylococcus aureus</i> , <i>Salmonella typhimurium</i> , and <i>Bacillus cereus</i>	50
Date extract	Phenolic acids and flavonoids	<i>Escherichia coli</i> , <i>Bacillus subtilis</i> , <i>Enterococcus faecalis</i> , and <i>Salmonella</i> spp.	51
Walnut green husk extract	Phenolic compounds	<i>Staphylococcus aureus</i> , <i>Bacillus cereus</i> , <i>Bacillus subtilis</i>	52
Almond skin extract	Polyphenols	<i>Staphylococcus aureus</i> , <i>Listeria monocytogenes</i>	53
Tomato seeds extract	Metabolites such as fatty acids, carotenoids, saponins, and phenolic compounds	<i>Staphylococcus aureus</i> , <i>Salmonella enteritidis</i> , <i>Micrococcus luteus</i> , <i>Enterococcus faecalis</i> , <i>Bacillus cereus</i> , and <i>Candida albicans</i>	54
Buckwheat hull extract	Phenolics, flavonoids, antioxidants comprising tocopherols, rutin, and quercetin derivatives	Gram-positive (<i>Bacillus cereus</i> , <i>Staphylococcus aureus</i> , <i>Enterococcus faecalis</i>) and Gram-negative bacteria (<i>Salmonella choleraesuis</i> , <i>Escherichia coli</i> , and <i>Proteus mirabilis</i>)	55
Pummelo peel extract	Flavonoids	<i>Escherichia coli</i> , <i>Pseudomonas aeruginosa</i> , <i>Bacillus subtilis</i> , <i>Staphylococcus aureus</i> , <i>Chromobacterium violaceum</i> , and <i>Vibrio anguillarum</i>	56

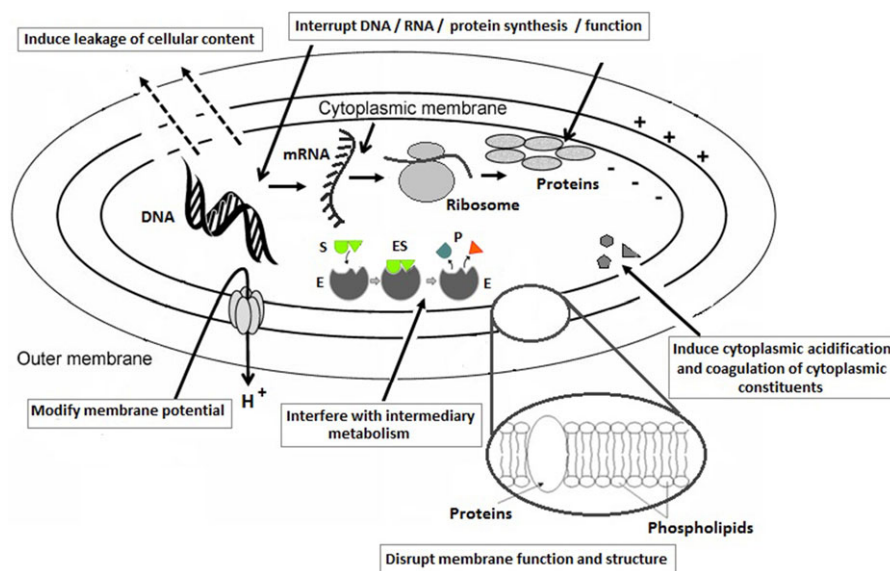


Figure 2. Different sites of action of antimicrobial polyphenols at the cellular level.

mechanism of action of antimicrobials at real time at the single-cell level.⁹¹ Flow cytometric analysis revealed that resveratrol-*trans*-dihydrodimer disturbs the membrane potential and hinders DNA synthesis of microorganisms.⁹² Paulo *et al.*⁹³ used microscopic analysis combined with flow cytometry to determine the bacteriostatic effect of 200 mg L⁻¹ resveratrol (4 × minimal inhibitory concentration (MIC) for *Bacillus cereus* and 2 × MIC for *Staphylococcus aureus* at 1–2 × 10⁸ CFU mL⁻¹) against Gram-positive bacteria. Modifications in cell morphology and DNA were observed in the presence of resveratrol; it can thus be assumed that it interferes with the cell cycle of bacteria. Duggirala *et al.*⁹⁴ screened 11 natural phenolics for the inhibition of the bacterial division protein FtsZ and identified coumarins as promising candidates. Recently, Liu *et al.*³¹ observed that sublethal treatments of *Listeria monocytogenes* cells with olive leaf extract abolished flagella and thereby reduced their motility. Other antibacterial mechanisms of action of phenolic-rich plant extracts, such as inhibition of quorum sensing, which is involved in pathogenesis of many food bacteria, cannot be excluded; such an antibacterial mechanism of action was recently reported for oregano essential oil.⁹⁵ The modes of action of polyphenols discussed earlier are diverse, and this can be advantageous for their application as natural antimicrobial agents. However, further studies in this field are needed to obtain the rationale for their utilization as antimicrobial food additives. For instance, transcriptomic analysis of microbial cells treated with sublethal doses of plant phenolics or plant extracts should be performed to identify genes whose expression would be modified. For instance, quantitative polymerase chain reaction (qPCR) analysis of the expression of genes in *Escherichia coli* O157:H7 following treatment with cranberry concentrate allowed observation of the downregulation of genes coding for bacterial membrane and cell wall constituent synthesis.⁹⁶

USES OF ANTIMICROBIAL PLANT POLYPHENOLS IN FOODS

Antimicrobial activity of plant polyphenols in foods

The food use of plant extracts has been shown to be promising, and some of these extracts already possess a generally recognized

as safe (GRAS) status. A comprehensive document regarding the use of phytochemicals as food preservatives has been developed by the International Life Sciences Institute-Europe:⁹⁷ it is focused on their effective identification and characterization. However, the recent increase in natural preservative use has induced changes in European legislation (EC/1334/2008)⁹⁸ implemented in January 2011. These changes include new statements for natural extracts and treatments used for their preparation. At the same time, there is a need to highlight processes that are more environmentally friendly than the usual methods. In the Code of Federal Regulations, Title 21, the Food and Drug Administration (FDA)⁹⁹ defines safe natural additives for food use according to the following statements: (i) they are used in the minimum quantity required to produce their intended physical or technical effect and in accordance with all the good manufacturing practice principles; (ii) in the appropriate forms (plant parts, fluid and solid extracts, concentrates, absolutes, oils, gums, balsams, resins, oleoresins, waxes, and distillates), they can be used alone or in combination with flavoring substances and GRAS adjuvants in food. Many plant-derived products have thus been proposed as food ingredients or supplements, and they take an interesting place in the market among other healthy products.

Beverages (water- and tea-based drinks, yogurts and smoothies) are the most common foods fortified with polyphenols.¹⁰⁰

In addition to their antioxidant activity, a great deal of effort has recently been made to include polyphenols in natural functional ingredients as food antimicrobial preservatives.¹⁰¹

Plants synthesize polyphenols in response to stress because of their self-defense from diseases mainly induced by microorganisms. That is why they are considered a promising source of antimicrobials with healthy features. Many natural phenolics that are widespread in nature, especially those that are extracted from edible plants and that have proven antimicrobial activities, could be used as potential food preservatives.^{9,19,102–104}

The antibacterial activity of three pure compounds naturally occurring in plants, caffeic acid, *p*-coumaric acid, and rutin, in different food products was tested by Stojkovic *et al.*¹⁰⁴ Amounts of *p*-coumaric and caffeic acids above 0.1 g L⁻¹ completely inhibited *Staphylococcus aureus* growth in chicken soup, and after 72 h, no cell survival was observed in samples treated with greater than

0.9 g L⁻¹ rutin and stored at either 25 or 4 °C. Phenolic compounds have a relevant role in the visual appearance (pigmentation and browning), taste (astringency) and odor (aromas) of plant-derived products.^{105,106} Interestingly, sensory evaluation for overall acceptance revealed that compared to those of the control samples, the sensory features of chicken soup and pork meat exposed to *p*-coumaric acid and caffeic acid were well appreciated.¹⁰⁴

The antibacterial effect of gallic acid combined with caffeic acid, rutin and quercetin against *Escherichia coli* was investigated in a meat model system at 4 °C. This combination of phenolics at a concentration of 100 or 200 mg L⁻¹ was bactericidal after 14 or 21 days of incubation. Such a synergistic effect makes it possible to enhance the activity of the polyphenols and reduce their effective concentration.¹⁰⁷

The antimicrobial potency of pinosylvin was evaluated in different food systems:¹⁹ 25–200 mg kg⁻¹ pinosylvin caused a decrease of 2–4 log of *Enterobacteriaceae* in fermenting sauerkraut. The antimicrobial activity of pinosylvin (140 mg kg⁻¹) against *Listeria monocytogenes* inoculated in fresh gravlax was higher at 8 °C than at 20 °C. *Saccharomyces cerevisiae* inoculated in strawberry jam was completely eliminated by 300 mg kg⁻¹ pinosylvin. However, 75 mg L⁻¹ pinosylvin was sufficient to completely inhibit *Staphylococcus aureus* growth in culture media, while 200 mg L⁻¹ pinosylvin had no effect in milk.

Numerous *in vitro* studies have been performed in microbiological culture media to assess the antimicrobial activity of plant extracts, but far fewer studies have addressed their application to food products. The lower antimicrobial efficacy of plant extracts in real foods may be the reason for this imbalance of information.⁷² The presence of the glycosyl groups of flavonoids contained in the crude extracts is partially responsible for the reduction in their activity against a wide range of bacteria reported in several studies.^{90–92,108,109,110}

In situ evaluation of the antimicrobial activity of plant extracts is crucial for food use because of interactions of their bioactive compounds with food components, most likely reducing their effectiveness. However, *in vitro* screening remains a first step to identify the antimicrobial potential of plants. An antimicrobial efficacy similar to that in *in vitro* cultures could be achieved by adding higher amounts of plant extract to foods.⁵⁸ Two-fold, ten-fold, 50-fold, and 25–100-fold higher plant extract concentrations were necessary to have the same antimicrobial effect in skimmed milk (from 0.6 g kg⁻¹ to 10 g kg⁻¹ for rosemary extract),¹¹¹ in pork liver sausage (from 5 to 50 mL kg⁻¹ for rosemary extract against *Listeria monocytogenes*),¹¹² and in soft cheese (from 0.04 to 2.5 mL kg⁻¹ for a mixture of rosemary, sage and citrus extracts against *Listeria monocytogenes*),¹¹³ respectively, as in *in vitro* trials.^{2,114} For instance, Miceli *et al.*¹¹⁵ observed that a ten-fold increase in the quantity of *Borago officinalis* (from 10 to 100 g L⁻¹) and *Brassica juncea* (from 3.1 to 31 g L⁻¹) aqueous extracts was necessary to achieve an antimicrobial effect in meat, fish, and vegetables. This variance can result from the interactions that occur in food systems between hydrophobic bioactive constituents of plant extracts and major food ingredients such as fat and proteins. Based on their hydrophilic character, other phytochemicals behave differently in food products. The dose of phenolics applied for food preservation should be set with sensory considerations and not based solely on *in situ* antimicrobial efficacy. To be accepted as food preservatives, phenolic-rich plant extracts should not strongly impart their typical color and flavor to foods. Ideally, the plant extract is chosen according to culinary associations already existing in consumer

behaviors (e.g. rosemary for meat,¹¹² thyme for vegetable and chicken soups⁶⁰).

In food matrices rich in fat, a lipid coating that wraps the microorganisms and protects them from antimicrobials can form.⁷¹ Uhart *et al.*¹¹⁶ reported that spices inactivate *Salmonella* Typhimurium DT104 under *in vitro* conditions, whereas a decrease in their inhibition efficacy was observed when the spices were included in complex food matrices (e.g. ground beef). Similarly, green and jasmine tea did not significantly reduce *Listeria monocytogenes*, *Staphylococcus aureus* or total bacterial counts in ground beef.¹¹⁷

In addition, compared to culture media, many foodstuffs have a reduced water content, which may limit the transport of antimicrobials into the microbial cells.⁷¹ Other potential causes include modifications in the solubility and charge of phenolics and variations in the cell envelope of target bacteria. The known interaction of many polyphenols with proteins might result in polyphenol–protein complexation (as reviewed by Papadopoulou and Frazier¹¹⁸) and thus limit the action of active polyphenolic compounds against microbial cells. Food-mimicking matrices prepared by dispersing proteins and/or fat in liquid media can help estimate the minimum concentrations inhibiting or killing microorganisms (minimum inhibitory concentrations (MICs) or minimum bactericidal concentrations (MBCs) for bacteria, respectively) in food systems.

The physiological state of target microorganisms in foods is also likely an important factor affecting the *in situ* efficiency of many antimicrobials: most *in vitro* antimicrobial activity assays are performed with microorganisms in an optimal environment without any limiting substrates to allow their exponential growth, which is not the case in real foods.

Some phenolic-containing aqueous plant extracts that have exhibited a broad antimicrobial spectrum (among those that were non-toxic and had a relatively limited odor and taste) and that have already been used for direct incorporation in foods or in food packaging materials in the past 15 years are listed in Table 2.

Stability of plant polyphenols

Polyphenol stability is a crucial property for application in food systems and is a function of several factors, such as size, chemical structure, water solubility and polarity. Recently, nutrition has become a tool to promote human health, and maximal knowledge of the effects of treatment processes is essential for maintaining the functions of plant biomolecules not only as food preservatives but also as compounds of nutritional interest.⁷²

For the application of phenolic compounds for food preservation, they have to be stable until the expiration date of the product to which they were added. However, polyphenols are relatively unstable when directly applied in foods. The stability of such compounds in food systems can be attributed to a series of stabilities: physical, chemical, colloidal, and biological, which are correlated with each other.¹⁵⁹

Co-extrusion of a linear low density polyethylene (LLDPE)-based film blended with grape seed extract (10 g kg⁻¹) in a twin-screw extruder with a barrel temperature ranging from 160 to 190 °C resulted in a strong reduction in the antimicrobial activity of the extract.¹⁶⁰ Conversely, a polyethylene-based film blended with pomegranate peel extract (15 g kg⁻¹) and produced by the same process demonstrated good antimicrobial activity in another work.¹⁶¹

Polyphenol stability in solution depends on environmental factors (e.g. pH, electrolyte composition, and presence of oxidants). The instability of phenolic compounds can occur at pH 1–11,

Table 2. Some studies regarding the application of aqueous phenolic-rich plant extracts to food preservation in the past 15 years

Food group	Plant extract	Microorganisms	References
Meat and poultry	Capsicum extract Lemon/cherry/vinegar extract	<i>Salmonella typhimurium</i>	119 120
		<i>Pseudomonas aeruginosa</i> <i>Listeria monocytogenes</i>	
Meat products	Rosemary/oregano extracts	Total viable counts	121 122 123
		Psychrotrophic bacterial counts	
		<i>Pseudomonas</i> spp.	
		Lactic acid bacteria	
Beef slices	Oregano/cranberry extracts	Total viable counts	124
		Bacterial spoilage	125
		<i>Bacillus cereus</i>	126
Beef meat balls	Rosemary/orange/lemon extracts	<i>Pseudomonas aeruginosa</i>	
		<i>Escherichia coli</i> O157:H7	
Fried meat	Oregano and thyme, oregano with marjoram and thyme with sage	<i>Listeria monocytogenes</i>	
		Spoilage microorganisms: <i>Staphylococcus aureus</i> , <i>Lactobacillus</i> spp., <i>Brochothrix thermosphacta</i> , <i>Pseudomonas</i> spp., <i>Escherichia coli</i>	127
Chilled steak	Water spice extracts: clove, cinnamon, star anise, pricklyash peel and common fennel	<i>Escherichia coli</i> O157:H7	128,129 130 131 132 96
		<i>Listeria monocytogenes</i> Scott A	
Ground beef	Grape seed extract pine bark, rosemary oleoresin extract Oregano/cranberry (50:50) extract Water-soluble arrowroot tea extract Dried plum puree Cranberry concentrate	<i>Salmonella typhimurium</i>	
		<i>Listeria monocytogenes</i> Scott A, <i>Salmonella typhimurium</i>	
		<i>Salmonella enteritidis</i> , <i>Listeria monocytogenes</i>	
		<i>Escherichia coli</i> , <i>Salmonella</i>	
		<i>Listeria monocytogenes</i>	
Beef patties	Grape pomace extract Pomegranate peel extract	<i>Enterobacteriaceae</i> and coliforms, lipolytic bacteria, <i>Salmonella</i> , <i>Staphylococcus aureus</i> , yeasts and molds	43 36
		<i>Listeria monocytogenes</i>	
Meat surfaces	Oregano/pimento extract	<i>Listeria monocytogenes</i>	133,134 135
		<i>Escherichia coli</i> O157:H7 <i>Pseudomonas</i> spp.	
Cured cooked meat model system	Cranberry/cherry/lime/grape seed extracts Cinnamon stick/oregano/clove/pomegranate peel/grape seed extracts	<i>Listeria monocytogenes</i>	136
		<i>Listeria monocytogenes</i>	137
Raw pork	Cinnamon stick/oregano/clove/pomegranate peel/grape seed extracts	<i>Staphylococcus aureus</i>	
		<i>Salmonella enterica</i>	
Fresh pork sausages	Rosemary extract/chitosan/alpha-tocopherol	<i>Enterobacteriaceae</i> , <i>Pseudomonas</i> spp., yeasts and molds, lactic acid bacteria	1 38
		<i>Listeria monocytogenes</i>	139 120
Ham	Rosemary extract Lemon/cherry/vinegar extract	<i>Listeria monocytogenes</i>	140 141 142
		Total bacterial count, Coliforms	
Chicken meat	Pomegranate peel extract Oregano extract	<i>Staphylococcus aureus</i>	
		<i>Campylobacter jejuni</i>	
Chicken meat juice	Rosemary extract	<i>Campylobacter jejuni</i>	142
		Aerobic plate count	143
Chicken sausage	Fresh garlic powder	<i>Listeria monocytogenes</i>	36
Chicken liver patties	Pomegranate (<i>Punica granatum</i>) peel extract		

Table 2. Continued

Food group	Plant extract	Microorganisms	References
Raw turkey meat balls	Sage extract Lemon/cherry/vinegar extract	Mesophilic bacteria Coliforms <i>Listeria monocytogenes</i> <i>Listeria monocytogenes</i>	144 120
Ready-to-eat vacuum-packaged diced turkey <i>Fish</i>	Rosemary extract		139
Fresh chilled fish	Pomegranate peel extract	<i>Listeria monocytogenes</i>	33
Cold fish filet	Oregano and cranberry	<i>Listeria monocytogenes</i>	124
Smoked fish	Coffee pulp smoke	Coliforms and fungal counts	145
Salami	<i>Eremophila duttonii</i> and <i>Eremophila alternifolia</i> extracts	<i>Listeria monocytogenes</i>	146
Cooked shrimp and raw tuna	Pomegranate peel extract	<i>Vibrio parahemolyticus</i>	147
<i>Dairy</i>			
Full cream milk, skim milk	<i>Eremophila duttonii</i> and <i>Eremophila alternifolia</i> extracts	<i>Listeria monocytogenes</i>	146
Pasteurized cow milk	Extract of mango seed kernel	Coliforms, <i>Escherichia coli</i>	49
Yogurt stew	Citrus flowers extract	<i>Escherichia coli</i> O157:H7, <i>Pseudomonas aeruginosa</i> , <i>Staphylococcus aureus</i> , <i>Bacillus subtilis</i>	148
Kalari cheese	Pomegranate rind extract	Total plate count, psychrophilic count, yeast and mold counts, coliforms	149
Pate and brie cheese	<i>Eremophila duttonii</i> and <i>Eremophila alternifolia</i> extracts	<i>Listeria monocytogenes</i>	146
<i>Vegetables</i>			
Tomatoes	Grape seed extract	<i>Listeria monocytogenes</i> Scott A <i>Listeria innocua</i> ATCC 33090	48
Carrots	Hydrosol of thyme, black cumin, sage, rosemary and bay leaf extracts	<i>Salmonella typhimurium</i> <i>Escherichia coli</i> O157:H7	150
Salad vegetables	Unripe grape juice	<i>Salmonella typhimurium</i>	151
Vegetable soup	Grape pomace	<i>Staphylococcus aureus</i> , <i>Escherichia coli</i>	152
<i>Rice</i>			
Rice cakes	Green tea/rosemary extract	<i>Bacillus cereus</i> , <i>Staphylococcus aureus</i>	153
<i>Fruits</i>			
Murcott tangor fruits	<i>Anadenanthera colubrine</i> extract	<i>Alternaria alternata</i>	154
'Rocha' pears	<i>Origanum vulgare</i> extract	<i>Botrytis cinerea</i> , <i>Penicillium expansum</i>	155
Apple	Hydrosol of thyme, black cumin, sage, rosemary and bay leaf extract	<i>Salmonella typhimurium</i> , <i>Escherichia coli</i> O157:H7	150
Fresh-cut apples	Ethanollic extract of cinnamon bark	<i>Escherichia coli</i> O157:H7, <i>Listeria innocua</i>	156
<i>Juice</i>			
Fresh-squeezed tomato juice	Extract of pine needles	Total counts of viable bacteria, <i>Escherichia coli</i> , <i>Proteus vulgaris</i> , <i>Staphylococcus aureus</i> , <i>Bacillus subtilis</i> , <i>Bacillus cereus</i>	157
Wine	Extracts from eucalyptus leaves and almond skins	Lactic acid bacteria	158

favorable for oxidative degradation, complex formation and reactions with other phenols, amino acids, proteins, and metal ions.^{162,163} However, pH changes may induce new structures and colors of phenolics (the red wine pigment malvidin 3-glucoside may change from red at pH 1 to colorless at pH 4–5, to purple at pH 6–7, and to yellow at pH 7–8¹⁶³).

The OH groups located on the benzene ring of phenolic compounds are often involved in responses to pH variations. Ultra-violet spectral monitoring allowed Friedman and Jurgens¹⁶³ to observe that in contrast to caffeic, chlorogenic and gallic acids (with two or three OH groups attached to the benzene ring), conjugated non-phenolic aromatic acids such as *trans*-cinnamic acid without any OH groups are stable at high pH (pH 11).

Other structural criteria play a role in promoting the complexation of phenolics with other solutes at high pH values and thus induce their instability. For instance, more complex phenolics with multiring aromatic structures such as catechin, epigallocatechin, and rutin have ionized and resonance forms that are more resistant to degradation by pH than monocyclic compounds.¹⁶³ The number of OH groups located on the benzene ring can indicate the ability of phenolics to form quinone oxidation products. Ferulic acid with no more than one OH group is stable at high pH (pH 7–11), whereas caffeic acid is unstable to pH variations because of the two adjacent phenolic OH groups on the benzene ring.¹⁶³ Not only the number of OH groups but also their presence on the same or separate aromatic rings and their position (meta- or ortho-position) affect the ability of phenolics to interact with each other via conjugation or quinone formation. The spatial arrangement of OH groups is reported to influence the stabilities to pH variations.^{163,164}

The phenolic acids caffeic acid, chlorogenic acid, and gallic acid have been found to be irreversibly affected by high pH values.¹⁶³ Conversely, an acidic pH had no effect on chlorogenic acid stability after inclusion in apple juice. Other phenolics, such as (–)-catechin, (–)-epigallocatechin, ferulic acid, rutin, and *trans*-cinnamic acid, may resist pH-induced degradation.¹⁶³ Concerning anthocyanins, it is well known that variations in pH significantly influence their stability and color.¹⁶³

Curcumin is primarily used as a food additive (coloring agent: E100 (i)), but it is increasingly considered a multifunctional bioactive molecule. Interestingly, glycosylated¹⁶⁵ or amino acid-conjugated¹⁶⁶ curcumin have shown similar antibacterial, antioxidant and antimutagenic activities as pure curcumin, so such chemical modifications did not affect the earlier mentioned bioactive properties of curcumin. However, microcapsules of curcumin (prepared with gelatin and porous starch by the spray-drying method) have better solubility and stability than free curcumin along with similar antibacterial and antifungal activities.¹⁶⁷

Colloidal stability is defined as the ability of polyphenols to maintain a homogeneous dispersion in food matrices under various storage conditions. The stability of polyphenols added to complex food matrices can be predicted based on information on various interactions that can occur with surrounding components present in foods. Repulsive forces among charged groups may prevent polymerization and aggregation of these active compounds. Through the choice of the appropriate formulation of phenolic extracts, the formed electrostatic repulsive forces may thus increase the stability of the system once incorporated into the foods.

Biological stability includes the ability of polyphenols to preserve their antioxidant and antimicrobial properties after processing and for long-term storage under the same conditions. Room

or refrigerated temperatures are the environmental conditions in which polyphenol activities are usually evaluated. To preserve their bioactivity, polyphenols can be freeze-dried. Many bioactive molecules can undergo chemical degradation, isomerization or polymerization during harsh food processes such as baking, steaming and extrusion, thereby possibly inducing a loss of their activities.¹⁰¹

When incorporated into food matrices, phenolic compounds may be subjected to temperature variations. The matrix nature is the most influential factor in the thermal stability of botanical compounds in foods. Normally, phenolic compounds with higher melting temperatures are more stable to heat processing, but the effect of heat can be more pronounced in the presence of other food ingredients. A pure aqueous solution of chlorogenic acid (207–209 °C melting temperature) has been found to be stable to heat treatment (1 h at 90 °C)¹⁶³, while the loss (leaching out or decomposition) of chlorogenic acid heated (30 min at 100 °C or 18 min at 121 and 204 °C) in the presence of food constituents was reported by other authors.^{168,169} Heat-treated (100 °C, 15 min) drumstick leaf extracts showed a significant decrease in their antioxidant activity compared to that of untreated samples. In contrast, the antioxidant activity of carrot tuber extract was not affected by the same heat treatment.¹⁷⁰ In some cases, heat treatment (105 °C, 20 min) induced the formation of new molecules, which either reduce, preserve or even improve the antimicrobial activity of different plant extracts.^{171,172} For instance, new phenolics with low molecular weights were found in heated grape seed extracts.¹⁷³ However, it was reported that the polyphenol content of foods decreases in response to thermal processing and long-term storage.^{174,175} The thermal stability of polyphenols in apple juice was studied by Spanos *et al.*¹⁷⁶ and van der Sluis *et al.*¹⁷⁷ Cinnamic acid, procyanidin and quercetin contents have been found to decrease when apple juice was stored at room temperature. Compared to freeze-dried grape seeds, grape seeds that were heat-dried at 100 and 140 °C exhibited 18.6% and 32.6% decreases in total polyphenols, respectively.¹⁷⁸ Heating at 60 °C or above for 8 h dramatically reduced the procyanidin and anthocyanin contents in freeze-dried grape pomace.¹⁷⁹

Some studies have suggested heat-stable plant extracts that could be used as food preservatives, such as cinnamon in cookies;¹⁸⁰ *Garcinia* extract;¹⁸¹ grape, amla, and drumstick leaf extracts¹⁸² in biscuits; and mango fiber concentrate (with 16.1 mg g⁻¹ of soluble polyphenols) in bread and cookies.¹⁸³

Successful food product development is deeply based on the nature of the interactions that may occur between the ingredients of food.¹⁰¹ A strong interaction between grape seed procyanidins and proteins leads to the formation of protein–tannin aggregates. The molecular weight and polymerization degree of procyanidins increase this aggregation.¹⁸⁴ Carvalho *et al.*¹⁸⁵ indicated that this type of binding is influenced by the protein properties (molecular size, hydrophobicity and structural flexibility), the polyphenol properties (degree of polymerization, extent of galloylation, structural flexibility) and environmental factors (temperature, pH, ionic strength, presence of organic solvents and presence of carbohydrates). Since the astringent taste of polyphenol-rich fruits and vegetables,¹⁰⁶ haze in beverages¹⁸⁶ and the bioavailability reduction in both food protein and polyphenols^{118,187} depend on tannin–protein interactions, these interactions are the most studied polyphenol–protein interactions. Some studies have used bovine serum albumin, while others used α -lactalbumin.¹⁸⁸

The storage of polyphenols for a long time under specific environmental conditions such as high temperature and light

exposure could seriously affect their chemical and physical stabilities. With respect to long-term storage, two phenomena must be considered in food systems: (i) the polyphenol components may be altered by oxidation, and (ii) the physical structure of polyphenols may be influenced by polymerization. Normally, oxidative damage is hardly a problem in practice, but it can be minimized by protection from light and air using an inert atmosphere as a preventive measure to maintain the effective biological activity of compounds.

Reducing sugars¹⁸⁹ or different carbohydrates¹⁹⁰ (e.g. trehalose) are commonly used as antioxidants in foods. Komes *et al.*¹⁹⁰ showed that due to its glass transition property, trehalose can retain and preserve hydrophobic phenolic compounds of fresh fruits during dehydration processes.

Other phytochemicals and antioxidants intentionally introduced to a food system may help to stabilize polyphenols.⁷² Vitamin C added to processed yellow passion fruit exerted a protective effect on plant chemicals.¹⁹¹ Red clover leaf extracts were demonstrated to make anthocyanins more stable when added to muscadine wines during storage (20 and 37 °C for 9 weeks).¹⁹² Lecithin addition to tea catechin solution at acidic pH and room temperature has the ability to protect tea catechins from oxidative damage.¹⁹³

High-performance liquid chromatography (HPLC) coupled with mass spectrometry (MS) analysis is usually used to assess the stability of polyphenols (e.g. molecular structure and quantity).¹⁹⁴

Quantitative structure–activity relationship (QSAR) studies can be used to predict and determine the extract formulations that would be more stable in different food matrices. Indeed, the QSAR approach has already been used to determine the structure–reactivity and structure–antimicrobial activity relationships of phenols under different conditions by evaluating different parameters.¹⁹⁵ In this way, QSAR analysis can provide information on how interactions between phenolics or with other molecules (proteins, lipids, oxygen, etc.) modulate their antimicrobial activity.

Release of plant polyphenols from active edible coatings or packaging materials to foods in direct contact

To alleviate the deficiencies in using plant phenolic compounds in foods, polyphenols can be added to the immediate zone of foods in direct contact through slow release from edible coatings or packaging materials. Such systems could maintain an efficient concentration of antimicrobial plant phenolics in the superficial zone of foods over time. This approach could be advantageous for foods such as raw muscle foods (fish fillets, meat pieces) or some fruit and vegetables for which most microbial contamination occurs in their superficial zone. One advantage of edible coatings or food-contact packaging materials with antimicrobial plant phenolics over their direct spraying is their controlled release over time. Various studies on the use of active films and edible coatings to deliver antimicrobial agents to the surface of a wide range of foods in contact (fruit, vegetables, and meat products) have been conducted.^{196,197} The delivery of phenolic compounds from edible coatings is mainly described as a sequence of material transfer movement starting with diffusion, followed by desorption from the film's or coating's surface, sorption of the compounds at the interface and finally sorption into the food.^{198–203} It has been acknowledged that the delivery rate of bioactive compounds from films or edible coatings to food is faster when the release is a consequence of their swelling or dissolution, which is conditioned by the nature of the food matrix in direct contact and the polymer matrix of film or coating.²⁰⁰ Furthermore, the

time and temperature of contact,²⁰⁴ the polymer matrix (promoting or no interaction) with phenolics via functional groups,^{199,201,203} the properties (chemical structure and polarity)²⁰⁰ of the phenolic compounds (migrating substances), and their contents in the edible films have been reported to affect the migration rate through coatings to foods in contact.^{198,199,202,205} Additionally, the microstructure of the polymer matrix²⁰⁶ and the way in which the phenolic compounds are oriented with respect to the food based on their hydrophilic or hydrophobic properties strongly affect their migration and thus their effectiveness in protecting foods in contact. Edible coating or active packaging design should thus exploit the possibility of tuning the physicochemical interactions between antimicrobial plant phenolics and the polymers, which are the main components of edible coatings/packaging materials, to control their release kinetics. Another potential advantage of edible coatings/packaging materials incorporating antimicrobial plant phenolics is their increased stability to oxidation in these polymeric matrices. Packaging materials made of edible biopolymers combined with natural antimicrobials are favorable for making foods safer and of higher quality.²⁰¹ The association of antimicrobial agents with edible coatings has thus increasingly been considered a favorable approach to increase the shelf life and/or enhance the safety of perishable foods in recent decades. This trend is illustrated by the increase in the proportion of articles on edible coatings that also consider antimicrobials in the Web of Science® database from 0% before 1994 to 25% since 2010.

Edible coatings/films incorporating antimicrobial plant polyphenols

Edible coating/film formulations are based on only food ingredients and additives. On the one hand, an edible coating is described as a thin layer of edible material formed directly on the superficial zone of a food that can be consumed with the food product. To prepare edible coatings, film-forming suspensions can be applied to foods by various processes, as reviewed by Andrade *et al.*²⁰⁷ (e.g. panning, fluidized bed, dipping, spraying). A subsequent draining of excess film-forming suspension and drying are necessary following the dipping of food products. On the other hand, stand-alone edible films may be prepared by either solvent-casting or extrusion-blowing methods. Cast films can be prepared by pouring a film-forming suspension on a flat substratum, which is subsequently dried. Most edible films are prepared using this versatile technology at the laboratory scale. However, at the industrial scale, most food packaging plastic films are prepared by extrusion-blow molding. Edible films can also be prepared with this technology.²⁰⁸

Edible coatings/films provide a barrier to gaseous exchange as well as the transmission of moisture, flavors and other soluble constituents of processed products when manipulated and stored, thereby enhancing their shelf life.²⁰⁹ The use of edible coatings/films as vectors of bioactive molecules can ensure their availability to act effectively at their site of action.²¹⁰ Incorporation into edible coatings/films is a good alternative to preserve bioactive compounds such as antimicrobial phenolics in foods. Bioactive compounds can be incorporated (i) on the external surface of the film, (ii) on the internal surface of the film, (iii) in the multilayers of the edible coatings, or (iv) in different parts of the film.²⁶

Zein, whey proteins, caseinates, soy proteins, chitosan, alginate, carrageenan, pullulan, pectin, cellulose, and its derivatives are examples of biopolymers that have been used to prepare edible films and coatings.^{211–219} These coatings and films can delay food spoilage due to their gas barrier properties, their intrinsic activity

(e.g. the antifungal activity of chitosan) or the antimicrobial compounds added to their formulation. Therefore, in addition to the biodegradability of these natural biopolymers, such films and coatings are considered environmentally friendly since they could contribute to food waste reduction.

Recent studies dealing with the incorporation of antimicrobial plant extracts into edible films and coatings are listed in Table 3. The incorporation of such compounds into films may enhance their antimicrobial activity;²³¹ the uptake of a sufficient quantity of phytochemicals on the surface of foods over time could be made possible by their gradual release through the film.⁵⁸

In the literature, antimicrobial packaging acts primarily on foodborne pathogenic bacteria such as *Listeria monocytogenes*, *Staphylococcus aureus*, *Escherichia coli* O157:H7, and *Salmonella* spp.^{232–234} However, food spoilage microorganisms such as *Bacillus* spp. and *Lactobacillus* spp. could also be targeted²²⁸ to increase perishable food shelf life and/or contribute to food waste reduction.

The release of antimicrobials from the edible coatings depends on many attributes, such as electrostatic (ionic and hydrogen bonds) and hydrophobic interactions between antimicrobials and polymers, osmosis, structural modifications of the polymeric matrix resulting from the presence of the antimicrobial agents, and the surrounding conditions (temperature, pH).⁷¹

Coatings may be used as a system for releasing antimicrobial phytochemicals over time on a wide range of food surfaces (e.g. vegetables, fruit, and meat products).⁷¹ Rapeseed protein/gelatin coatings containing grape seed extract have been used to inhibit *Escherichia coli* O157:H7 and *Listeria monocytogenes* growth in strawberries.²³⁵ Edible zein coatings applied to fruit and vegetables have been found to have a protective effect during storage (by controlling their respiration, ripening, and senescence).²⁰¹ Some phenolic acids (gallic, vanillic, and cinnamic acids) and extracts from clove, oregano, artichoke stems and walnut shells were assessed as antimicrobial zein film additives against four plant pathogenic bacteria.²⁰¹ The incorporation of phenolic compounds (10–40 g m⁻²) into zein films was shown to improve the porosity of films, which became more flexible and lost their brittleness.

Chitosan-coated films incorporated with green tea extract (40 g kg⁻¹) had bactericidal activity against *Listeria monocytogenes* in ham steak for 8 weeks of storage at 4 °C.²³⁶ In a more recent study, incorporation of green tea extract (5–10 g L⁻¹) considerably enhanced the antifungal activity of chitosan coatings on fresh walnut kernel; fungal growth was not detected during 18 weeks of storage at room temperature.²³⁷

Food packaging materials incorporating antimicrobial plant polyphenols

Although conventional plastic packaging raises environmental concerns and its current use in direct contact with foods is highly regulated, many studies regarding active food packaging consider polyethylene or polypropylene and their derivatives due to their excellent physical and chemical characteristics.^{161,238,239} Such active packaging falls under the scope of the EC 450/2009 regulation.²⁴⁰

At the industrial scale, there are two possible processes for including antimicrobials in packaging materials: (i) direct incorporation into the polymers during extrusion by melt-blending²⁴¹ and (ii) coating of the antimicrobial agents onto polymer surfaces.^{242,243} Extrusion is preferred by manufacturers because of the high cost of the coating process (additional steps and technical changes).²⁴⁴ However, additional costs may also result from the degradation

of actives during extrusion processes operating at high temperature, which would have to be compensated for by the addition of a higher amount of active ingredients.²⁴¹ Moreover, the fact that antimicrobials are equally spread throughout the entire thickness of films made by extrusion can lead to limitations in their release from the packaged material and therefore lower *in situ* activity.²⁴¹ Therefore, in addition to the question of the stability of antimicrobial plant phenolics to the conditions prevailing during melt blending with the polymer (high temperature and shear stress), the transport properties of the plant phenolics once incorporated into the polymeric matrix of the packaging material also must be considered. The amount of plant phenolics released and their release kinetics should effectively inhibit the multiplication of unwanted microorganisms in the superficial zone of food.

Adequate analytical methods to assay plant phenolics in active food packaging materials and monitor their release in food matrices in direct contact should thus be developed. Therefore, Colon and Nerin²⁴⁵ developed a method to quantify tea compounds released from a polyethylene terephthalate (PET) film with an internal coating layer containing green tea extract to IV gamma nectarines placed in a tray covered by this active film. Solid-phase extraction (SPE) combined with ultra-performance liquid chromatography (UPLC)-MS was used to check that the amounts of catechins and caffeine from the green tea extract delivered by the packaging material were below the migration limits of 10 µg per kg of nectarine. In agreement with the European Union (EU) regulations for food-contact materials (EU 10/2011⁹⁸ and EC 450/2009²⁴⁰), all components not available in the positive lists of the regulations introduced and not specifically recognized as a food additive, such as catechins and caffeine, must be below 10 µg per kg of food or food simulant. The ability of packaging films composed of cast polypropylene/polyvinyl alcohol incorporated with rhubarb ethanolic extracts and cinnamon essential oil to preserve the quality of fresh beef was investigated. Interestingly, all the experimental cast films used significantly decreased the total viable counts (TVCs).²⁴⁶ However, as stated earlier, preparation of cast films by solvent evaporation, despite likely limiting essential oil loss by evaporation during the preparation of stand-alone films, is not the preferred method. In another study, 15 g kg⁻¹ pomegranate peel extract was blended with polyethylene resin by twin-screw extrusion at 160–190 °C to obtain active films.¹⁶¹ A decrease in total volatile basic nitrogen (TVB-N) was observed during refrigerated storage of fresh pork meat packaged in these active films. The shelf life of the fresh pork meat was thus extended by 3 days. Interestingly, this result suggests that pomegranate peel extract still had significant antimicrobial and antioxidant activities following its incorporation by extrusion in polyethylene films. Despite its promise, this type of practice is still in its infancy.^{247,248}

CONCLUSION

The *in vitro* antibacterial activity of many phenolic-rich plant extracts and pure plant phenolics has been reported in this review. Although their activity in perishable foods is often reduced or even lost, numerous examples of plant extracts or phenolics effectively preventing microbial contamination or degradation of foods are given. Since no pure plant phenolics are authorized as food preservatives, only direct incorporation of edible plant extracts (i.e. food ingredients) into perishable foods can be considered currently. In addition to direct incorporation into perishable food matrices, incorporation into the polymeric matrix of either food packaging materials or edible coatings is a promising approach to deliver

Table 3. Examples of edible coatings incorporated with antimicrobial plant extracts

Antimicrobial plant extract	Biopolymer	Target microorganisms	Coated food	References
Grape seed extract	Sodium alginate	<i>Micrococcus luteus</i> , <i>Listeria monocytogenes</i> , <i>Staphylococcus aureus</i> , <i>Escherichia coli</i> , <i>Salmonella enteritidis</i>	-	220
Grape seed extract	Soy protein isolate	<i>Listeria monocytogenes</i> , <i>Escherichia coli</i> O157:H7		221
Wine grape pomace water extract	Low-methoxyl pectin, sodium alginate, Ticaflm®	<i>Listeria innocua</i> , <i>Escherichia coli</i>	-	222
Apple skin extract	Acai	<i>Listeria monocytogenes</i>	-	223
Guarana seed ethanolic extract	Gelatin and chitosan	<i>Staphylococcus aureus</i> , <i>Escherichia coli</i>	-	224
Boldo-do-chile (<i>Peumus boldus</i> Molina) leaf ethanolic extract	Gelatin and chitosan	<i>Staphylococcus aureus</i> , <i>Escherichia coli</i>	-	224
Cinnamon bark ethanolic extract	Gelatin and chitosan	<i>Staphylococcus aureus</i> , <i>Escherichia coli</i>	-	224
Rosemary leaves ethanolic extract	Gelatin and chitosan	<i>Staphylococcus aureus</i> , <i>Escherichia coli</i>	-	224
Oregano aqueous extract	Porcine skin gelatin	Aerobic plate counts (15 °C)	Cold-smoked sardine muscle	225
Rosemary aqueous extract	Porcine skin gelatin	Aerobic plate counts (15 °C)	Cold-smoked sardine muscle	225
<i>Satureja thymbra</i> ethyl acetate extract	Carboxymethyl cellulose (CMC)	Total viable count, <i>Pseudomonas</i> spp., <i>Enterobacteriaceae</i> spp.	Fresh gilthead seabream (<i>Sparus aurata</i>) fillets	226
Sweet basil hydroalcoholic extract	Pullulan	<i>Rhizopus arrhizus</i>	Jonagored apples	227
<i>Satureja hortensis</i> L. water extract	Pullulan	<i>Staphylococcus aureus</i> , <i>Bacillus subtilis</i> , <i>Salmonella enteritidis</i> , <i>Escherichia coli</i> , <i>Penicillium expansum</i>	Pepper, apples	228
<i>Quillaja saponaria</i> Mol. hydroalcoholic extract	Milk proteins (calcium caseinate and whey protein isolate)	<i>Botrytis cinerea</i>	Fresh strawberries	229
Moringa plant extract	CMC	<i>Colletotrichum gloeosporioides</i> , <i>Alternaria alternata</i> , <i>Lasiodiplodia theobromae</i>	Avocado fruit	230

active plant phenolics to the immediate zone of foods in direct contact. However, again, due to the absence of active plant phenolics from the positive list of food preservatives and the legislation regarding active food packaging, only the application of edible coatings made of biopolymers with a food ingredient or additive status and edible plant extracts with a food ingredient status can be considered today. In addition to evaluation of some plant phenolics as new food preservatives, future research on building a rationale for the application of phenolic-rich plant extracts or phenolics for food preservation should specifically focus on (i) identifying the molecular mechanisms underlying their ability to control unwanted microorganisms, (ii) understanding the effect of food microstructure and composition on their antimicrobial activity and (iii) designing innovative and sustainable systems of delivery of active phenolics preserving their stability before use and favoring their controlled release in the superficial zone of perishable foods where postprocessing microbial contamination mainly occurs.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the French National Agency for Research (ANR-14-CE20-0005-01 ACTIPHEN) for the financial support of this work.

DECLARATION 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.

AUTHOR CONTRIBUTIONS

All authors listed have made substantial, direct and intellectual contribution to the work and approved it for publication.

REFERENCES

- Carocho M, Barreiro MF, Morales P and Ferreira ICFR, Adding molecules to food, pros and cons: a review on synthetic and natural food additives. *Comp Rev Food Sci Food Saf* **13**:377–399 (2014).
- Burt S, Essential oils: their antibacterial properties and potential application in foods: a review. *Int J Food Microbiol* **94**:223–253 (2004).
- Hyltdgaard M, Mygind T and Meyer RL, Essential oils in food preservation: mode of action, synergies, and interactions with food matrix components. *Front Microbiol* **3**:12 (2012).
- Tomas-Barberan FA and Robins RJ, *Phytochemistry of Fruit and Vegetables*. Clarendon Press, Oxford (1997).
- Cuvelier ME, Richard H and Berset C, Antioxidative activity and phenolic composition of pilot-plant and commercial extracts of sage and rosemary. *J Am Oil Chem Soc* **73**:645–652 (1996).
- Cevallos-Casals BA, Byrne D, Okie WR and Cisneros-Zevallos L, Selecting new peach and plum genotypes rich in phenolic compounds and enhanced functional properties. *Food Chem* **96**:273–280 (2006).
- Food and Agriculture Organization (FAO), Global food losses and food waste—extent, causes and prevention. *Report of FAO Meeting*, Rome, FAO (2011).
- Chen Z and Jiang X, Microbiological safety of chicken litter or chicken litter-based organic fertilizers: a review. *Agriculture* **4**:1–29 (2014).
- Engels C, Schieber A and Ganzle MG, Sinapic acid derivatives in defatted Oriental mustard (*Brassica juncea* L.) seed meal extracts using UHPLC-DAD-ESIMS and identification of compounds with antibacterial activity. *Eur Food Res Technol* **234**:535–542 (2012).
- Borges A, Ferreira C and Saavedra MJ, Antibacterial activity and mode of action of ferulic and gallic acids against pathogenic bacteria. *Microb Drug Resist* **19**:256–265 (2013).
- Díaz-Gómez R, López-Solís R, Obreque-Slier E and Toledo-Araya H, Comparative antibacterial effect of gallic acid and catechin against *Helicobacter pylori*. *LWT Food Sci Technol* **54**:331–335 (2013).
- Ozcelik B, Orhan DD, Ozgen S and Ergun F, Antimicrobial activity of flavonoids against extended-spectrum β -lactamase (ES β L)-producing *Klebsiella pneumoniae*. *Trop J Pharm Res* **7**:1151–1157 (2008).
- Orhan DD, Ozcelik B, Ozgen S and Ergun F, Antibacterial, antifungal, and antiviral activities of some flavonoids. *Microbiol Res* **165**:496–504 (2010).
- Rattanachaiyunsopon P and Phumkhachorn P, Contents and antibacterial activity of flavonoids extracted from leaves of *Psidium guajava*. *J Med Plants Res* **4**:393–396 (2010).
- Scalbert A, Antimicrobial properties of tannins. *Phytochemistry* **30**:3875–3883 (1991).
- Chung KT, Wong TY, Wei CI, Huang YW and Lin Y, Tannins and human health: a review. *Crit Rev Food Sci Nutr* **38**:421–464 (1998).
- Engels C, Knodler M, Zhao YY, Carle R, Ganzle MG and Schieber A, Antimicrobial activity of gallotannins isolated from mango (*Mangifera indica* L.) kernels. *J Agric Food Chem* **57**:7712–7718 (2009).
- Jung HJ, Hwang IA and Sung WS, Fungicidal effect of resveratrol on human infectious fungi. *Arch Pharm Res* **28**:557–560 (2005).
- Plumed-Ferrer C, Väkeväinen K, Komulainen H, Rautiainen M, Smeds A, Raitanen JE *et al.*, The antimicrobial effects of wood-associated polyphenols on food pathogens and spoilage organisms. *Int J Food Microbiol* **164**:9–107 (2013).
- Cowan MM, Plant products as antimicrobial agents. *Clin Microbiol Rev* **12**:564–582 (1999).
- Singh DN, Verma N, Raghuvanshi S, Shukla PK and Kulshreshtha DK, Antifungal anthraquinones from *Saprosma fragrans*. *Bioorg Med Chem Lett* **16**:4512–4514 (2006).
- Ignacimuthu S, Pavunraj M, Duraipandiyan V, Raja N and Muthu C, Antibacterial activity of a novel quinone from the leaves of *Pergularia daemia* (Forsk, a traditional medicinal plant). *Asian J Tradit Med* **4**:36–40 (2009).
- Basile A, Sorbo S, Spadaro V, Bruno M, Maggio A, Faraone N *et al.*, Antimicrobial and antioxidant activities of coumarins from the roots of *Ferulago campestris* (Apiaceae). *Molecules* **14**:939–952 (2009).
- Saleem M, Nazir M and Ali MS, Antimicrobial natural products: an update on future antibiotic drug candidates. *Nat Prod Rep* **27**:238–254 (2010).
- Venugopala KN, Rashmi V and Odhav B, Review on natural coumarin lead compounds for their pharmacological activity. *Biomed Res Int*, Article ID 14 **2013**:963248 (2013).
- Quirós-Sauceda AE, Ayala-Zavala JF, Olivas GI and González-Aguilar GA, Edible coatings as encapsulating matrices for bioactive compounds: a review. *J Food Sci Technol Mysore* **51**:1674–1685 (2014).
- Monente C, Bravo J, Vitas AI, Arbillaga L, Paz De Peña M and Cid C, Coffee and spent coffee extracts protect against cell mutagens and inhibit growth of food-borne pathogen microorganisms. *J Funct Foods* **12**:365–374 (2015).
- Sung SH, Kim KH, Jeon BT, Cheong SH, Park JH and Kim DH, Antibacterial and antioxidant activities of tannins extracted from agricultural by-products. *J Med Plants Res* **6**:3072–3079 (2012).
- Granato D, do Prado-Silva L, Alvarenga VO, AAF Z, Bataglion GA, de Moraes DR *et al.*, Characterization of binary and ternary mixtures of green, white and black tea extracts by electrospray ionization mass spectrometry and modeling of their *in-vitro* antibacterial activity. *LWT Food Sci Technol* **65**:414–420 (2016).
- Friedman M, Henika PR and Levin CE, Bactericidal activities of health promoting, food-derived powders against the foodborne pathogens *Escherichia coli*, *Listeria monocytogenes*, *Salmonella enterica*, and *Staphylococcus aureus*. *J Food Sci* **78**:270–275 (2013).
- Liu Y, McKeever LC and Malik NSA, Assessment of the antimicrobial activity of olive leaf extract against foodborne bacterial pathogens. *Front Microbiol* **8**:113 (2017).
- Zorić N, Kopjar N, Kraljić K, Oršolić N, Tomić S and Kosalec I, Olive leaf extract activity against *Candida albicans* and *C. dubliniensis* - the *in-vitro* viability study. *Acta Pharm* **66**:411–421 (2016).
- Al-Zoreky N, Antimicrobial activity of pomegranate (*Punica granatum* L.) fruit peels. *Int J Food Microbiol* **134**:244–248 (2009).
- Gullon B, Pintado ME, Perez-Alvarez JA and Viuda-Martos M, Assessment of polyphenolic profile and antibacterial activity

- of pomegranate peel (*Punica granatum*) flour obtained from co-product of juice extraction. *Food Control* **59**:94–98 (2016).
- 35 Agourram A, Ghirardello D, Rantsiou K, Zeppa G, Belviso S and Romane A, Phenolic content, antioxidant potential and antimicrobial activities of fruit and vegetable by-product extracts. *Int J Food Prop* **16**:1092–1104 (2013).
 - 36 Hayrapetyan H, Hazeleger WC and Beumer RR, Inhibition of *Listeria monocytogenes* by pomegranate (*Punica granatum*) peel extract in meat pate at different temperatures. *Food Control* **23**:66–72 (2012).
 - 37 Li G, Xu Y, Wang X, Zhang B, Shi C, Zhang W *et al.*, Tannin-rich fraction from pomegranate rind damages membrane of *Listeria monocytogenes*. *Foodborne Pathog Dis* **11**:1–7 (2014).
 - 38 Devatkal SK, Jaiswal P, Jha SN, Bharadwaj R and Viswas KN, Antibacterial activity of aqueous extract of pomegranate peel against *Pseudomonas stutzeri* isolated from poultry meat. *J Food Sci Technol* **50**:555–560 (2013).
 - 39 Rosas-Burgos EC, Burgos-Hernández A, Noguera-Artiaga L, Kacániová M, Hernández-García F, Cárdenas-López JL *et al.*, Antimicrobial activity of pomegranate peel extracts as affected by cultivar. *J Sci Food Agric* **97**:802–810 (2017).
 - 40 Pagliarulo C, de Vito V, Picariello G, Colicchio R, Pastore G, Salvatore P *et al.*, Inhibitory effect of pomegranate (*Punica granatum* L.) polyphenol extracts on the bacterial growth and survival of clinical isolates of pathogenic *Staphylococcus aureus* and *Escherichia coli*. *Food Chem* **190**:824–831 (2016).
 - 41 Friedman M, Antibacterial, antiviral, and antifungal properties of wines and winery byproducts in relation to their flavonoid content. *J Agric Food Chem* **62**:6025–6042 (2014).
 - 42 Jara-Palacios MJ, Gonzalez-Manzano S, Escudero-Gilete ML, Hernandez D, Dueñas M, González-Paramás AM *et al.*, Study of Zalema grape pomace: phenolic composition and biological effects in *Caenorhabditis elegans*. *J Agric Food Chem* **61**:5114–5121 (2013).
 - 43 Sagdic O, Ozturk I, Yilmaz MT and Yetim H, Effect of grape pomace extracts obtained from different grape varieties on microbial quality of beef patty. *J Food Sci* **76**:515–521 (2011).
 - 44 García-Lomillo J, González-SanJosé ML, Del Pino-García R, Rivero-Pérez MD and Muñoz-Rodríguez P, Antioxidant and antimicrobial properties of wine byproducts and their potential uses in the food industry. *J Agric Food Chem* **62**:12595–12602 (2014).
 - 45 Mingo E, Silvan JM and Martínez-Rodríguez AJ, Selective antibacterial effect on *Campylobacter* of a winemaking waste extract (WWE) as a source of active phenolic compounds. *LWT Food Sci Technol* **68**:418–424 (2016).
 - 46 Silván JM, Mingo E, Hidalgo M, de Pascual-Teresa S, Carrascosa AV and Martínez-Rodríguez AJ, Antibacterial activity of a grape seed extract and its fractions against *Campylobacter* spp. *Food Control* **29**:25–31 (2013).
 - 47 Bevilacqua A, Ficelo S, Corbo MR and Sinigaglia M, Bioactivity of grapefruit seed extract against *Pseudomonas* spp. *J Food Process Preserv* **34**:495–507 (2010).
 - 48 Bisha B, Weinstetel N and Brehm-Stecher BF, Antilisterial effects of gravinol-s grape seed extract at low levels in aqueous media and its potential application as a produce wash. *J Food Prot* **73**:266–273 (2010).
 - 49 Abdalla AEM, Darwish SM, Ayad EHE and El-Hamahmy RM, Egyptian mango by-product 1. Compositional quality of mango seed kernel. *Food Chem* **103**:1134–1140 (2007).
 - 50 Jabria MA, Rtibib K, Ben-Saida A, Aouadhic C, Hosnid K, Saklya M *et al.*, Antidiarrhoeal, antimicrobial and antioxidant effects of myrtle berries (*Myrtus communis* L.) seeds extract. *J Pharm Pharmacol* **68**:264–274 (2016).
 - 51 Kchaou W, Abbès F, Ben Mansour R, Blecker C, Attia H and Besbes S, Phenolic profile, antibacterial and cytotoxic properties of second grade date extract from Tunisian cultivars (*Phoenix dactylifera* L.). *Food Chem* **194**:1048–1055 (2016).
 - 52 Oliveira I, Sousa A, Ferreira IC, Bento A, Estevinho L and Pereira JA, Total phenols, antioxidant potential and antimicrobial activity of walnut (*Juglans regia* L.) green husks. *Food Chem Toxicol* **46**:2326–2331 (2008).
 - 53 Mandalari G, Bisignano C, D'Arrigo M, Ginestra G, Arena A, Tomaino A *et al.*, Antimicrobial potential of polyphenols extracted from almond skins. *Lett Appl Microbiol* **51**:83–89 (2010).
 - 54 Taveira M, Silva LR, Vale-Silva LA, Pinto E, Valentao P and Ferreres F, *Lycopersicon esculentum* seeds: an industrial byproduct as an antimicrobial agent. *J Agric Food Chem* **58**:9529–9536 (2010).
 - 55 Cabarkapa IS, Sedej IJ, Sakac MB, Saric LC and Plavsic DV, Antimicrobial activity of buckwheat (*Fagopyrum esculentum* Moench) hulls extract. *Food Process Qual Saf* **35**:159–163 (2008).
 - 56 Liu Z, Pan Y, Li X, Jie J and Zeng M, Chemical composition, antimicrobial and anti-quorum sensing activities of pummelo peel flavonoid extract. *Ind Crops Prod* **109**:862–868 (2017).
 - 57 Lai PK and Roy J, Antimicrobial and chemopreventive properties of herbs and spices. *Curr Med Chem* **11**:1451–1460 (2004).
 - 58 Knobloch K, Weigand N, Weiss HM and Wogenschow H, in *Progress in Essential Oil Research*, ed. by Brunke EJ. Walter de Gruyter, Berlin, p. 249 (1986).
 - 59 Dorman HJ and Deans SG, Antimicrobial agents from plants: antibacterial activity of plant volatile oils. *J Appl Microbiol* **88**:308–316 (2000).
 - 60 Ultee A, Bennik MH and Moezelaar R, The phenolic hydroxyl group of carvacrol is essential for action against the food-borne pathogen *Bacillus cereus*. *Appl Environ Microbiol* **68**:1561–1568 (2002, 2002).
 - 61 Sikkema J, de Bont JAM and Poolman B, Interactions of cyclic hydrocarbons with biological membranes. *J Biol Chem* **269**:8022–8028 (1994).
 - 62 Gyawali R and Ibrahim SA, Natural products as antimicrobial agents. *Food Control* **46**:412–429 (2014).
 - 63 Pauli A and Knobloch K, Inhibitory effects of essential oil components on growth of food-contaminating fungi. *Z Lebensm Unters Forsch* **185**:10–13 (1987).
 - 64 Pelczar MJ, Chan ECS and Krieg NR, *Microbiology*, 5th edn. McGraw-Hill Book Co, New York, NY (1986).
 - 65 Kurita N, Miyaji M, Kurane R, Takahara Y and Ichimura K, Antifungal activity and molecular orbital energies of aldehyde compounds from oils of higher plants. *Agric Biol Chem* **43**:2365–2371 (1979).
 - 66 Ikigai H, Nakae T, Hara Y and Shimamura T, Bactericidal catechins damage the lipid bilayer. *Biochim Biophys Acta* **1147**:132–136 (1993).
 - 67 Maherani B, Arab-Tehrany E, Kheiriloomoo A, Geny D and Linder M, Calcein release behavior from liposomal bilayer; influence of physicochemical/mechanical/structural properties of lipids. *Biochimie* **95**:2018–2033 (2013).
 - 68 Fichert T, Yazdaniyan M and Proudfoot JR, A structure–permeability study of small drug-like molecules. *Bioorg Med Chem Lett* **13**:719–722 (2003).
 - 69 El Maghraby GMM, Williams AC and Barry BW, Drug interaction and location in liposomes: correlation with polar surface areas. *Int J Pharm* **292**:179–185 (2005).
 - 70 Radulovic NS, Blagojevic PD, Stojanovic-Radic ZZ and Stojanovic NM, Antimicrobial plant metabolites: structure diversity and mechanism of action. *Curr Med Chem* **20**:932–952 (2013).
 - 71 da Cruz Cabral L, Fernández Pinto V and Patriarca A, Application of plant derived compounds to control fungal spoilage and mycotoxin production in foods. *Int J Food Microbiol* **166**:1–14 (2013).
 - 72 Negi PS, Plant extracts for the control of bacterial growth: efficacy, stability, and safety issues for food application. *Int J Food Microbiol* **156**:7–17 (2012).
 - 73 Ratledge C and Wilkinson SG, *Microbial Lipids*. Academic Press, London (1988).
 - 74 Vaara M, Agents that increase the permeability of the outer membrane. *Microbiol Rev* **56**:395–411 (1992).
 - 75 Inouye S, Yamaguchi H and Takizawa T, Screening of the antibacterial effects of variety of essential oils on respiratory tract pathogens, using a modified dilution assay method. *J Infect Chemother* **7**:251–254 (2001).
 - 76 Helander IM, Alakomi H, Latva-Kala K, Mattila-Sandholm T, Pol I, Smid EJ *et al.*, Characterization of the action of selected essential oil components on Gram-negative bacteria. *J Agric Food Chem* **46**:3590–3595 (1998).
 - 77 Lambert RJW, Skandamis PN, Coote PJ and Nychas GJE, A study of the minimum inhibitory concentration and mode of action of oregano essential oil, thymol and carvacrol. *J Appl Microbiol* **91**:453–462 (2001).
 - 78 La Stora A, Ercolini D, Marinello F, Di Pasqua R, Villani F and Mauriello G, Atomic force microscopy analysis shows surface structure changes in carvacrol-treated bacterial cells. *Res Microbiol* **162**:164–172 (2011).
 - 79 Djilani A and Dicko A, The therapeutic benefits of essential oils, in *Nutrition, Well-being and Health in Technology*, ed. by Bouayed J. IntechOpen, London, pp. 155–178 (2012).

- 80 Ya C, Gaffney SH, Lilley TH and Haslam E, Carbohydrate-polyphenol complexation, in *Chemistry and Significance of Condensed Tannins*, ed. by Hemingway RW and Karchesy JJ. Plenum Press, New York, NY, p. 553 (1988).
- 81 Chung KT, Lu Z and Chou MW, Mechanism of inhibition of tannic acid and related compounds on the growth of intestinal bacteria. *Food Chem Toxicol* **36**:1053–1060 (1998).
- 82 Tsuchiya H, Sato M, Miyazaki T, Fujiwara S, Tanigaki S, Ohyama M *et al.*, Comparative study on the antibacterial activity of phytochemical flavanones against methicillin-resistant *Staphylococcus aureus*. *J Ethnopharmacol* **50**:27–34 (1996).
- 83 Cushnie TP and Lamb AJ, Antimicrobial activity of flavonoids. *Int J Antimicrob Agents* **26**:343–356 (2005).
- 84 Mirzoeva OK, Grishanin RN and Calder PC, Antimicrobial action of propolis and some of its components: the effects on growth, membrane potential and motility of bacteria. *Microbiol Res* **152**:239–246 (1997).
- 85 Stapleton PD, Shah S and Hamilton-Miller JMT, Anti-*Staphylococcus aureus* activity and oxacillin resistance modulating capacity of 3-O-acylcatechins. *Int J Antimicrob Agents* **24**:374–380 (2004).
- 86 Sato M, Tanaka H, Yamaguchi R, Kato K and Etoh H, Synergistic effects of mupirocin and an isoflavanone isolated from *Erythrina variegata* on growth and recovery of methicillin resistant *Staphylococcus aureus*. *Int J Antimicrob Agents* **24**:241–246 (2004).
- 87 Haraguchi H, Tanimoto K, Tamura Y, Mizutani K and Kinoshita T, Mode of antibacterial action of retrochalcones from *Glycyrrhiza inflata*. *Phytochemistry* **48**:125–129 (1998).
- 88 Gradisar H, Pristovsek P, Plaper A and Jerala R, Green tea catechins inhibit bacterial DNA gyrase by interaction with its ATP binding site. *J Med Chem* **50**:264–271 (2007).
- 89 Zhang L, Kong Y, Wu D, Zhang H, Wu J, Chen J *et al.*, Three flavonoids targeting the hydroxyacyl-acyl carrier protein dehydratase from *Helicobacter pylori*: crystal structure characterization with enzymatic inhibition assay. *Protein Sci* **17**:1971–1978 (2008).
- 90 Kuete V, Alibert-Franco S and Elyong KO, Antibacterial activity against bacteria expressing a multidrug-resistant phenotype. *Int J Antimicrob Agents* **37**:156–161 (2011).
- 91 Léonard L, Bouarab L, Ouled Bouhedda B, Degraeve P and Oulahal N, Recent advances on multi-parameter flow cytometry to characterize antimicrobial treatments. *Front Microbiol* **7**:1225 (2016).
- 92 Mora-Pale M, Bhan N, Masuko S, James P, Wood J, McCallum S *et al.*, Antimicrobial mechanism of resveratrol-trans dihydrodimer produced from peroxidase-catalyzed oxidation of resveratrol. *Biotechnol Bioeng* **112**:2417–2428 (2015).
- 93 Paulo L, Ferreira S, Gallardo E, Queiroz JA and Domingues F, Antimicrobial activity and effects of resveratrol on human pathogenic bacteria. *World J Microbiol Biotechnol* **26**:1533–1538 (2010).
- 94 Duggirala S, Rakesh P, Nankar RP, Rajendran S and Doble M, Phytochemicals as inhibitors of bacterial cell division protein FtsZ: coumarins are promising candidates. *Appl Biochem Biotechnol* **174**:283–296 (2014).
- 95 Alvarez MV, Ortega-Ramirez LA, Gutierrez-Pacheco MM, Bernal-Mercado AT, Rodriguez-Garcia I, Gonzalez-Aguilar GA *et al.*, Oregano essential oil-pectin edible films as anti-*quorum sensing* and food antimicrobial agents. *Front Microbiol* **5**:699 (2014).
- 96 Wu VCH, Qiu X, de los Reyes BG, Lin CS and Pan Y, Application of cranberry concentrate (*Vaccinium macrocarpon*) to control *Escherichia coli* O157:H7 in ground beef and its antimicrobial mechanism related to downregulated *slp*, *hdeA* and *cfa*. *Food Microbiol* **26**:32–38 (2009).
- 97 Schilter B, Andersson C, Anton R, Constable A, Kleiner J, O'Brien J *et al.*, Guidance for the safety assessment of botanicals and botanical preparations for use in food and food supplements. *Food Chem Toxicol* **41**:1625–1649 (2003).
- 98 Commission Regulation (EU) n° 10/2011 of 14 January 2011 on plastic materials and articles intended to come into contact with food.
- 99 Food and Drug Administration (FDA), Agency Response Letter GRAS Notice No. GRN 000125. CFSAN/Office of Food Additive Safety, Silver Spring, MD: FDA (2003).
- 100 Buchwald-Werner S, Gartner C, Horlacher P and Schwarz G, Fortification with substances other than vitamins and minerals (polyphenols, carotenoids, fatty acids and phytosterols), in *Food Fortification and Supplementation Technology*, ed. by Ottaway PB. CRC Press, Boca Raton, FL, pp. 41–59 (2009).
- 101 Yu J and Ahmedna M, Functional components of grape pomace: their composition, biological properties and potential applications. *Int J Food Sci Technol* **48**:221–237 (2013).
- 102 Muthuswamy S and Rupasinghe HPV, Fruit phenolics as natural antimicrobial agents: selective antimicrobial activity of catechin, chlorogenic acid and phloridzin. *J Food Agric Environ* **5**:81–85 (2007).
- 103 Jayaraman P, Sakharkar MK, Lim CS, Tang TH and Sakharkar KR, Activity and interactions of antibiotic and phytochemical combinations against *Pseudomonas aeruginosa* *in vitro*. *Int J Biol Sci* **6**:556–568 (2010).
- 104 Stojkovic D, Petrovic J, Sokovic M, Glamoclija J, Kukic-Markovic J and Petrovic S, *In situ* antioxidant and antimicrobial activities of naturally occurring caffeic acid, *p*-coumaric acid and rutin, using food systems. *J Sci Food Agric* **93**:3205–3208 (2013).
- 105 Tomás-Barberán FA and Robins RJ, Phytochemistry of fruits and vegetables. *Proceedings of the Phytochemical Society of Europe*, Wotton-under-Edge: Oxford Science Publications, Clarendon Press (1997).
- 106 Payne C, Bowyer PK, Herderich M and Bastian SEP, Interaction of astringent grape seed procyanidins with oral epithelial cells. *Food Chem* **115**:551–557 (2009).
- 107 Rodriguez Vaquero MJ, Aredes Fernandez PA, Manca de Nadra MC and Strasser de Saad AM, Phenolic compound combinations on *Escherichia coli* viability in a meat system. *J Agric Food Chem* **58**:6048–6052 (2010).
- 108 Rhee J, Diaz Ricci JC, Bode J and Schugerl K, Metabolic enhancement due to plasmid maintenance. *Biotechnol Lett* **16**:881–884 (1994).
- 109 Kapoor N, Narain U and Misra K, Bioactive conjugates of curcumin having ester peptide, thiol and disulphide links. *J Sci Ind Res* **66**:647–650 (2007).
- 110 Parvathy KS, Negi PS and Srinivas P, Antioxidant, antimutagenic and antibacterial activities of curcumin- β -diglucoside. *Food Chem* **115**:265–271 (2009).
- 111 del Campo J, Amiot MJ and Nguyen-The C, Antimicrobial effect of rosemary extracts. *J Food Prot* **63**:1359–1368 (2000).
- 112 Pandit VA and Shelef LA, Sensitivity of *Listeria monocytogenes* to rosemary (*Rosmarinus officinalis* L.). *Food Microbiol* **11**:57–63 (1994).
- 113 Mendoza-Yepes MJ, Sanchez-Hidalgo LE, Maertens G and Marin-Iniesta F, Inhibition of *Listeria monocytogenes* and other bacteria by a plant essential oil (DMC) in Spanish soft cheese. *J Food Saf* **17**:47–55 (1997).
- 114 Naidu AS, Lactoperoxidase, in *Natural Food Antimicrobial Systems*, ed. by Naidu AS. CRC Press, Boca Raton, FL, pp. 103–132 (2000).
- 115 Miceli A, Aleo A, Corona O, Sardina MT, Mammaia C and Settanni L, Antibacterial activity of *Borago officinalis* and *Brassica juncea* aqueous extracts evaluated *in vitro* and *in situ* using different food model systems. *Food Control* **40**:157–164 (2014).
- 116 Uhart M, Maki N and Ravishanker S, Effect of spices on growth and survival of *Salmonella* Typhimurium DT 104 in ground beef stored at 4 and 8 °C. *J Food Saf* **26**:115–125 (2006).
- 117 Kim S, Ruengwilysup C and Fung DY, Antibacterial effect of water-soluble tea extracts on foodborne pathogens in laboratory medium and in a food model. *J Food Prot* **67**:2608–2612 (2004b).
- 118 Papadopoulou A and Frazier RA, Characterization of protein-polyphenol interactions. *Trends Food Sci Technol* **15**:186–190 (2004).
- 119 Careaga M, Fernandez E, Dorantes L, Mota L, Jaramillo ME and Hernandez-Sanchez H, Antibacterial activity of *Capsicum* extract against *Salmonella typhimurium* and *Pseudomonas aeruginosa* inoculated in raw beef meat. *Int J Food Microbiol* **83**:331–335 (2003).
- 120 Glass K and Sindelar J, *AMI Foundation Funded Final Report: Controlling Listeria monocytogenes in Natural, Ready-To-Eat Meat and Poultry Products*. [Online]. (2010). Available: <http://www.amif.org/research/07> [13 October 2015].
- 121 Camo J, Beltran JA and Roncales P, Extension of the display life of lamb with an antioxidant active packaging. *Meat Sci* **80**:1086–1091 (2008).
- 122 Djenane D, Sanchez-Escalante A, Beltran JA and Roncales P, Extension of the shelf life of beef steaks packaged in a modified atmosphere by treatment with rosemary and displayed under UV-free lighting. *Meat Sci* **64**:417–426 (2003).
- 123 Zinoviadou KG, Koutsoumanis KP and Biliaderis CG, Physico-chemical properties of whey protein isolate films containing oregano oil and

- their antimicrobial action against spoilage flora of fresh beef. *Meat Sci* **82**:338–345 (2009).
- 124 Lin YT, Labbe RG and Shetty K, Inhibition of *Listeria monocytogenes* in fish and meat systems by use of oregano and cranberry phytochemical synergies. *Appl Environ Microbiol* **70**:5672–5678 (2004).
 - 125 Fernandez-Lopez J, Zhi N, Aleson-Carbonell L, Perez-Alvarez JA and Kuri V, Antioxidant and antibacterial activities of natural extracts: application in beef meatballs. *Meat Sci* **69**:371–380 (2005).
 - 126 Du H and Li H, Antioxidant effect of Cassia essential oil on deep-fried beef during the frying process. *Meat Sci* **78**:461–468 (2008).
 - 127 Wang Q, Ou Z, Lei H, Zeng W, Ying Y and Bai W, Antimicrobial activities of a new formula of spice water extracts against foodborne bacteria. *J Food Process Preserv* **36**:374–381 (2012).
 - 128 Ahn JH, Grun IU and Mustapha A, Antimicrobial and antioxidant activities of natural extracts *in vitro* and in ground beef. *J Food Prot* **67**:148–155 (2004).
 - 129 Ahn JH, Grun IU and Mustapha A, Effects of plant extracts on microbial growth, color change, and lipid oxidation in cooked beef. *Food Microbiol* **24**:7–14 (2007).
 - 130 Apostolidis E, Kwon YI and Shetty K, Inhibition of *Listeria monocytogenes* by oregano, cranberry and sodium lactate combination in broth and cooked ground beef systems and likely mode of action through proline metabolism. *Int J Food Microbiol* **128**:317–324 (2008).
 - 131 Kim S and Fung DY, Antibacterial effect of water-soluble arrowroot (*Puerariae radix*) tea extracts on foodborne pathogens in ground beef and mushroom soup. *J Food Prot* **67**:1953–1956 (2004).
 - 132 Pszczola DE, Beefing up innovations for meat and poultry ingredients. *Food Technol* **56**:54–67 (2002).
 - 133 Mosqueda-Melgar J, Raybaudi-Massilia RM and Martin-Belloso O, Inactivation of *Salmonella enterica* Ser. enteritidis in tomato juice by combining of high-intensity pulsed electric fields with natural antimicrobials. *J Food Sci* **73**:47–53 (2008).
 - 134 Mosqueda-Melgar J, Raybaudi-Massilia RM and Martin-Belloso O, Combination of high-intensity pulsed electric fields with natural antimicrobials to inactivate pathogenic microorganisms and extend the shelf life of melon and watermelon juices. *Food Microbiol* **25**:479–491 (2008).
 - 135 Oussalah M, Caillet S, Salmieri S, Saucier L and Lacroix M, Antimicrobial and antioxidant effects of milk protein-based film containing essential oils for the preservation of whole beef muscle. *J Agric Food Chem* **52**:5598–5605 (2004).
 - 136 Xi Y, Sullivan GA, Jackson AL, Zhou GH and Sebranek JG, Use of natural antimicrobials to improve the control of *Listeria monocytogenes* in a cured cooked meat model system. *Meat Sci* **88**:503–511 (2011).
 - 137 Shan B, Yi-Zhong C, Brooks JD and Corke H, Antibacterial and antioxidant effects of five spice and herb extracts as natural preservatives of raw pork. *J Sci Food Agric* **89**:1879–1885 (2009).
 - 138 Georgantelis D, Ambrosiadis I, Katikou P, Blekas B and Georgakis SA, Effect of rosemary extract, chitosan and α -tocopherol on microbiological parameters and lipid oxidation of fresh pork sausages stored at 4°C. *Meat Sci* **76**:172–181 (2007).
 - 139 Ruiz A, Williams SK, Djeri N, Hinton JA and Rodrick GE, Nisin, rosemary, and ethylenediaminetetraacetic acid affect the growth of *Listeria monocytogenes* on ready-to-eat Turkey ham stored at four degrees celsius for sixty-three days. *Poult Sci* **88**:1765–1772 (2009).
 - 140 Kanatt SR, Chander R and Sharma A, Antioxidant and antimicrobial activity of pomegranate peel extract improves the shelf life of chicken products. *Int J Food Sci Technol* **45**:216–222 (2010).
 - 141 Chouliara E, Karatapanis A, Savvaidis IN and Kontominas MG, Combined effect of oregano essential oil and modified atmosphere packaging on shelf-life extension of fresh chicken breast meat, stored at 4°C. *Food Microbiol* **24**:607–617 (2007).
 - 142 Piskernik S, Klancnik A, Riedel C, Brondsted L and Mozina SS, Reduction of *Campylobacter jejuni* by natural antimicrobials in chicken meat-related conditions. *Food Control* **22**:718–724 (2011).
 - 143 Sallam KHI, Ishioroshi M and Samejima K, Antioxidant and antimicrobial effects of garlic in chicken sausage. *LWT Food Sci Technol* **37**:849–855 (2004).
 - 144 Karpińska-Tymoszczyk M, Effects of sage extract (*Salvia officinalis* L.) and a mixture of sage extract and sodium isoascorbate on the quality and shelf life of vacuum-packed Turkey meatballs. *J Muscle Foods* **18**:420–434 (2007).
 - 145 Adebawale B, Ogunjobi M, Olubamiwa O, Olusola-Taiwo M and Omidiran V, Quality improvement and value addition of processed fish (*Clarias gariepinus*) using phenolic compounds in coffee pulp smoke. *Int Res J Agric Sci Soil Sci* **2**:520–524 (2012).
 - 146 Owen RJ and Palombo EA, Anti-listerial activity of ethanolic extracts of medicinal plants, *Eremophila alternifolia* and *Eremophila duttonii*, in food homogenates and milk. *Food Control* **18**:387–390 (2007).
 - 147 Wu J, Jahncke ML, Eifert JD, O'Keefe SF and Welbaum GE, Pomegranate peel (*Punica granatum* L) extract and Chinese gall (*Galla chinensis*) extract inhibit *Vibrio parahaemolyticus* and *Listeria monocytogenes* on cooked shrimp and raw tuna. *Food Control* **59**:695–699 (2016).
 - 148 Hashemi SMB, Amininezhad R, Shirzadinezhad E, Farahani M and Yousefabad SHA, The antimicrobial and antioxidant effects of *Citrus aurantium* L. flowers (bahar narang) extract in traditional yoghurt stew during refrigerated stora. *J Food Saf* **36**:153–161 (2016).
 - 149 Mahajan D, Bhat ZF and Kumar S, Pomegranate (*Punica granatum*) rind extract as a novel preservative in cheese. *Food Biosci* **12**:47–53 (2015).
 - 150 Tornuk F, Cankurt H, Ozturk I, Sagdic O, Bayram O and Yetim H, Efficacy of various plant hydrosols as natural food sanitizers in reducing *Escherichia coli* O157:H7 and *Salmonella typhimurium* on fresh cut carrots and apples. *Int J Food Microbiol* **148**:30–35 (2011).
 - 151 Karapinar M and Sengun IY, Antimicrobial effect of koruk juice against *Salmonella typhimurium* on salad vegetables. *Food Control* **18**:702–706 (2007).
 - 152 Sagdic O, Ozturk I and Kisi O, Modeling antimicrobial effect of different grape pomace and extracts on *S. aureus* and *E. coli* in vegetable soup using artificial neural network and fuzzy logic system. *Expert Syst Appl* **39**:6792–6798 (2012).
 - 153 Lee SY, Gwon SY, Kim SJ and Moon BK, Inhibitory effect of commercial green tea and rosemary leaf powders on the growth of foodborne pathogens in laboratory media and oriental-style rice cakes. *J Food Prot* **71**:1107–1111 (2009).
 - 154 Costa Carvalho DD, Alves E, Barbosa Camargos R, Ferreira Oliveira D, Soares Scolforo JR, de Carvalho DA *et al.*, Plant extracts to control *Alternaria alternata* in *Murcott tangor* fruits. *Rev Iberoam Micol* **28**:173–178 (2011).
 - 155 Matos OC and Barreiro MG, Safety use of bioactive products of plant origin for the control of post harvested fungal diseases of “Rocha” pear. *IV Simposium Ibérico de Maduración e pós-colheita: Frutos Horticolas. Livro Actas*. Oeiras, Portugal pp. 525–529 (2004).
 - 156 Muthuswamy S, Rupasinghe HPV and Stratton GW, Antimicrobial effect of cinnamon bark extract on *Escherichia coli* O157:H7, *Listeria innocua* and fresh-cut apple slices. *J Food Saf* **28**:534–549 (2008).
 - 157 Zeng WC, He Q, Sun Q, Zhong K and Gao H, Antibacterial activity of water-soluble extract from pine needles of *Cedrus deodara*. *Int J Food Microbiol* **153**:78–84 (2012).
 - 158 González-Rompinelli EM, Rodríguez-Bencomo JJ, García-Ruiz A, Sánchez-Patán F, Martín-Álvarez PJ, Bartolomé B *et al.*, A winery-scale trial of the use of antimicrobial plant phenolic extracts as preservatives during wine ageing in barrels. *Food Control* **33**:440–447 (2013).
 - 159 Maherani B, Tehrani EA, Mozafari MR, Gaiani C and Linder M, Liposomes: a review of manufacturing techniques and targeting strategies. *Curr Nanosci* **7**:436–452 (2011).
 - 160 Ha JK, Kim Y and Lee D, Multilayered antimicrobial polyethylene films applied to the packaging of ground beef. *Packag Technol Sci* **14**:55–62 (2001).
 - 161 Hu S, Wang H, Han W, Ma Y, Shao Z and Li L, Development of double-layer active films containing pomegranate peel extract for the application of pork packaging. *J Food Process Eng* **40**:12388 (2016).
 - 162 Lapidot T, Harel S, Akiri B, Granit R and Kanner J, pH-dependent forms of red wine anthocyanins as antioxidants. *J Agric Food Chem* **47**:67–70 (1999).
 - 163 Friedman M and Jurgens HS, Effect of pH on the stability of plant phenolic compounds. *J Agric Food Chem* **48**:2101–2110 (2000).
 - 164 Mataga N and Kubota T, *Molecular Interactions and Electronic Spectra*. Marcel Dekker, New York, NY, 504 pp. (1970).
 - 165 Mazza J and Brouillard R, Recent development in the stabilization of anthocyanins in food products. *Food Chem* **25**:207–225 (1987).
 - 166 Parvathy KS, Negi PS and Srinivas P, Curcumin amino acid conjugates: synthesis, antioxidant and antimutagenic attributes. *Food Chem* **120**:523–530 (2010).
 - 167 Chuda Y, Suzuki M, Nagata T and Tsushida T, Contents and cooking loss of three quinic acid derivatives from garland (*Chrysanthemum coronarium* L.). *J Agric Food Chem* **46**:1437–1439 (1998).

- 168 Friedman M and Dao L, Effect of autoclaving and conventional and microwave baking on the ergot alkaloid and chlorogenic acid contents of morning glory (*Ipomoea-tricolor cav cv*) heavenly blue seeds. *J Agric Food Chem* **38**:805–808 (1990).
- 169 Wang Y, Lu Z, Wu H and Lv F, Study on the antibiotic activity of microcapsule curcumin against foodborne pathogens. *Int J Food Microbiol* **30**:71–74 (2009).
- 170 Arabshahi DS, Vishalakshi Devi D and Urooj A, Evaluation of antioxidant activity of some plant extracts and their heat, pH and storage stability. *Food Chem* **100**:1100–1105 (2007).
- 171 Manzocco L, Anese M and Nicoli MC, Antioxidant properties of tea extracts as affected by processing. *LWT Food Sci and Technol* **31**:694–698 (1998).
- 172 Nicoli MC, Anese M and Parpinel M, Influence of processing on the antioxidant properties of fruits and vegetables. *Trends Food Sci Technol* **10**:94–100 (1999).
- 173 Kim S-H, Jeong S-M, Park W-P, Nam KC, Ahn DU and Lee S-C, Effect of heating conditions of grape seeds on the antioxidant activity of grape seed extracts. *Food Chem* **97**:472–479 (2006).
- 174 Klimczak I, Malecka M, Szlachta M and Gliszczynska-Swiglo A, Effect of storage on the content of polyphenols, vitamin C and the antioxidant activity of orange juices. *J Food Compos Anal* **20**:313–322 (2007).
- 175 Hager TJ, Howard LR and Prior RL, Processing and storage effects on monomeric anthocyanins, percent polymeric colour, and antioxidant capacity of processed blackberry products. *J Agric Food Chem* **56**:689–695 (2008).
- 176 Spanos GA, Wrolstad RE and Heatherbell DA, Influence of processing and storage on the phenolic composition of apple juice. *J Agric Food Chem* **38**:1572–1579 (1990).
- 177 van der Sluis AA, Dekker MA and van Boekel JS, Activity and concentration of polyphenolic antioxidants in apple juice. 3. Stability during storage. *J Agric Food Chem* **53**:1073–1080 (2005).
- 178 Larrauri JA, Ruperez P and Saura-Calixto F, Effect of drying temperature on the stability of polyphenols and antioxidant activity of red grape pomace peels. *J Agric Food Chem* **45**:1390–1393 (1997).
- 179 Khanal RC, Howard LR and Prior RL, Effect of heating on the stability of grape and blueberry pomace procyanidins and total anthocyanins. *Food Res Int* **43**:1464–1469 (2010).
- 180 Badei AZM, El-Akel ATM, Faheid SMM and Mahmoud BSM, Application of some spices in flavoring and preservation of cookies. I. Antioxidant properties of cardamom, cinnamon and clove. *Deut Lebensm Rundsch* **98**:176–183 (2002).
- 181 Nandita BR, Jena BS and Prabhaskar P, Influence of natural antioxidants and their carry-through property in biscuit processing. *J Sci Food Agric* **89**:288–298 (2009).
- 182 Reddy V, Urooj A and Kumar A, Evaluation of antioxidant activity of some plant extracts and their application in biscuits. *Food Chem* **90**:317–321 (2005).
- 183 Vergara-Valencia N and Granados-Perez E, Fibre concentrate from mango fruit: characterization, associated antioxidant capacity and application as a bakery product ingredient. *LWT Food Sci Technol* **40**:722–729 (2007).
- 184 de Freitas VAP and Mateus N, Structural features of procyanidin interactions with salivary proteins. *J Agric Food Chem* **49**:940–945 (2001).
- 185 Carvalho E, Povoas MJ, Mateus N and de Freitas V, Application of flow nephelometry to the analysis of the influence of carbohydrates on protein-tannin interactions. *J Sci Food Agric* **86**:891–896 (2006).
- 186 Siebert KJ, Effects of protein-polyphenol interactions on beverage haze, stabilization and analysis. *J Agric Food Chem* **47**:353–362 (1999).
- 187 Skrabanja V, Laerke HN and Kreft I, Protein-polyphenol interactions and *in-vivo* digestibility of buckwheat groat proteins. *Eur J Physiol* **440**(Suppl.):129–131 (2000).
- 188 Prigent SVE, Voragen AGJ, van Koningsveld GA, Baron A, Renard CMG and Gruppenet H, Interactions between globular proteins and procyanidins of different degrees of polymerization. *J Dairy Sci* **92**:5843–5853 (2009).
- 189 Lichtenberg B, Liposomes: preparation, characterization, and preservation. *Methods Biochem Anal* **33**:337–462 (1988).
- 190 Komes D, Lovri T, Gani KK and Gracin L, Study of trehalose addition on aroma retention in dehydrated strawberry puree. *Food Technol Biotechnol* **41**:111–119 (2003).
- 191 Talcott ST, Percival SS, Pittet-Moore J and Celoria C, Phytochemical composition and antioxidant stability of fortified yellow passion fruit (*Passiflora edulis*). *J Agric Food Chem* **51**:935–941 (2003).
- 192 Talcott ST, Brenes CH, Pires DM and Pozo-Insfran DD, Phytochemical stability and color retention of copigmented and processed muscadine grape juice. *J Agric Food Chem* **51**:957–963 (2003).
- 193 Lin QL, Wang J, Qin D and Bjorn B, Influence of amphiphilic structures on the stability of polyphenols with different hydrophobicity. *Sci China Series B Chem* **50**:121–126 (2007).
- 194 Ramirez-Coronel MA, Marnet N, Kolli VK, Roussos S, Guyot S and Augur C, Characterization and estimation of proanthocyanidins and other phenolics in coffee pulp (*Coffea arabica*) by thiolytic-high-performance liquid chromatography. *J Agric Food Chem* **52**:1344–1349 (2004).
- 195 Dambolena JS, López AG, Meriles JM, Rubinstein HR and Zygadlo JA, Inhibitory effect of 10 natural phenolic compounds on *Fusarium verticillioides*. A structure-property-activity relationships study. *Food Control* **28**:163–170 (2012).
- 196 Devlieghere F, Vermeiren L and Debevere J, New preservation technologies: possibilities and limitations. *Int Dairy J* **14**:273–285 (2004).
- 197 Ye M, Neetoo H and Chen H, Control of *Listeria monocytogenes* on ham steaks by antimicrobials incorporated into chitosan-coated plastic films. *Food Microbiol* **25**:260–268 (2008).
- 198 Peng Y, Wu Y and Li Y, Development of tea extracts and chitosan composite films for active packaging materials. *Int J Biol Macromol* **59**:282–289 (2013).
- 199 Mayachiew P and Devahastin S, Effects of drying methods and conditions on release characteristics of edible chitosan films enriched with Indian gooseberry extract. *Food Chem* **118**:594–601 (2010).
- 200 Ganiari S, Choulitoudi E and Oreopoulou V, Edible and active films and coatings as carriers of natural antioxidants for lipid food. *Trends Food Sci Technol* **68**:70–82 (2017).
- 201 Alkan D and Yemenicioglu A, Potential application of natural phenolic antimicrobials and edible film technology against bacterial plant pathogens. *Food Hydrocoll* **55**:1–10 (2016).
- 202 Gomez-Estaca J, Montero P, Fernandez-Martin F, Aleman A and Gomez-Guillen MC, Physical and chemical properties of tuna-skin and bovine-hide gelatin films with added aqueous oregano and rosemary extracts. *Food Hydrocolloids* **23**:1334–1341 (2009).
- 203 Benbettaieb N, Tanner C, Cayot P, Karbowiak T and Debeaufort F, Impact of functional properties and release kinetics on antioxidant activity of biopolymer active films and coatings. *Food Chem* **242**:369–377 (2018).
- 204 Arvanitoyannis IS and Kotsanopoulos KV, Migration phenomenon in food packaging. Food-package interactions, mechanisms, types of migrants, testing and relative legislation-a review. *Food Bioprocess Technol* **7**:21–36 (2014).
- 205 Lopez de Dicastillo CL, Navarro R, Guarda A and Galotto MJ, Development of biocomposites with antioxidant activity based on red onion extract and acetate cellulose. *Antioxidants* **4**:533–547 (2015).
- 206 LaCoste A, Schaich KM, Zumbrennen D and Yam KL, Advancing controlled release packaging through smart blending. *Packag Technol Sci* **18**:77–87 (2005).
- 207 Andrade RD, Skurtys O and Osorio FA, Atomizing spray systems for application of edible coatings. *Comp Rev Food Sci Food Saf* **11**:323–337 (2012).
- 208 Belyamani I, Prochazka F and Assezat G, Production and characterization of sodium caseinate edible films made by blown-film extrusion. *J Food Eng* **121**:39–47 (2014).
- 209 Kester J and Fennema O, Edible films and coatings: a review. *Food Technol* **40**:47–59 (1986).
- 210 Pothakamury UR and Barbosa-Cánovas GV, Fundamental aspects of controlled release in foods. *Trends Food Sci Technol* **6**:397–406 (1995).
- 211 Coma V, Sebtli I, Pardon P, Deschamps A and Pichavant FH, Antimicrobial edible packaging based on cellulosic ethers, fatty acids, and nisin incorporation to inhibit *Listeria innocua* and *Staphylococcus aureus*. *J Food Prot* **64**:470–475 (2001).
- 212 Coma V, Martial-Gros A, Garreau S, Copinet A, Salin F and Deschamps A, Edible antimicrobial films based on chitosan matrix. *J Food Sci* **67**:1162–1169 (2002).
- 213 Sebtli I, Martial-Gros A, Carnet-Pantiez A, Grelier S and Coma V, Chitosan polymer as bioactive coating and film against *Aspergillus niger* contamination. *J Food Sci* **70**:100–104 (2005).

- 214 Joerger RD, Antimicrobial films for food applications: a quantitative analysis of their effectiveness. *Packag Technol Sci* **20**:231–273 (2007).
- 215 Rojas-Grau MA, Avena-Bustillos RJ, Olsen C, Friedman M, Henika PR and Martin-Belloso O, Effects of plant essential oils and oil compounds on mechanical, barrier and antimicrobial properties of alginate apple puree edible films. *J Food Eng* **81**:634–641 (2007).
- 216 Mendes de Souza P, Fernandez A, Lopez-Carballo G, Gavara R and Hernandez-Munoz P, Modified sodium caseinate films as releasing carriers of lysozyme. *Food Hydrocolloids* **24**:300–306 (2010).
- 217 Zhong Y, Cavender G and Zhao Y, Investigation of different coating application methods on the performance of edible coatings on Mozzarella cheese. *LWT Food Sci Technol* **56**:1–8 (2014).
- 218 Gniewosz M, Synowiec A, Krasniewska K, Przybyl JL, Baczek K and Węglarz Z, The antimicrobial activity of pullulan film incorporated with meadowsweet flower extracts (*Filipendulae ulmariae* flos) on postharvest quality of apples. *Food Control* **37**:351–361 (2014).
- 219 Colak BY, Gouanvé F, Degraeve P, Espuche E and Prochazka F, Study of the influences of film processing conditions and glycerol amount on the water sorption and gas barrier properties of novel sodium caseinate films. *J Membr Sci* **478**:1–11 (2015).
- 220 Cha DS, Choi JH, Chinnan MS and Park HJ, Antimicrobial film based on Na-alginate and κ -carrageenan. *LWT Food Sci Technol* **35**:715–719 (2002).
- 221 Sivarooban T, Hettiarachchy NS and Johnson MG, Physical and antimicrobial properties of grape seed extract, nisin, and EDTA incorporated soy protein edible films. *Food Res Int* **41**:781–785 (2008).
- 222 Deng Q and Zhao Y, Physicochemical, nutritional, and antimicrobial properties of wine grape (cv. Merlot) pomace extract-based films. *J Food Sci* **73**:309–317 (2011).
- 223 Espitia PJP, Avena-Bustillos RJ, Du WX, Chiou BS, Williams TG, Wood D *et al.*, Physical and antibacterial properties of acai edible films formulated with thyme essential oil and apple skin polyphenols. *J Food Sci* **79**:903–910 (2014).
- 224 Bonilla J and Sobral PJA, Investigation of the physico-chemical, antimicrobial and antioxidant properties of gelatin-chitosan edible film mixed with plant ethanolic extracts. *Food Biosci* **16**:17–25 (2016).
- 225 Gomez-Estaca J, Montero P, Gimenez B and Gomez-Guillen MC, Effect of functional edible films and high pressure processing on microbial and oxidative spoilage in cold-smoked sardine (*Sardina pilchardus*). *Food Chem* **105**:511–520 (2007).
- 226 Choulitoudi E, Bravou K, Bimpilas A, Tsironi T, Tsimogiannis D, Taoukis P *et al.*, Antimicrobial and antioxidant activity of *Satureja thymbra* in gilthead seabream fillets edible coating. *Food Bioprod Process* **100**:570–577 (2016).
- 227 Synowiec A, Gniewosz M, Krasniewska K, Przybyl JL, Baczek K and Węglarz Z, Antimicrobial and antioxidant properties of pullulan film containing sweet basil extract and an evaluation of coating effectiveness in the prolongation of the shelf life of apples stored in refrigeration conditions. *Innov Food Sci Emerg Technol* **23**:171–181 (2014).
- 228 Krasniewska K, Gniewosz M, Synowiec A, Przybyl JL, Baczek K and Węglarz Z, The use of pullulan coating enriched with plant extracts from *Satureja hortensis* L. to maintain pepper and apple quality and safety. *Postharvest Biol Technol* **90**:63–72 (2014).
- 229 Zuniga GE, Junqueira-Goncalves MP, Pizarro M, Contreras R, Tapia A and Silva S, Effect of ionizing energy on extracts of *Quillaja saponaria* to be used as an antimicrobial agent on irradiated edible coating for fresh strawberries. *Radiat Phys Chem* **81**:64–69 (2012).
- 230 Tesfay SZ, Magwazaa LS, Mbilic N and Mditshwa A, Carboxyl methylcellulose (CMC) containing moringa plant extracts as new postharvest organic edible coating for Avocado (*Persea americana* Mill.) fruit. *Sci Hortic* **226**:201–207 (2017).
- 231 Appendini P and Hotchkiss JH, Review of antimicrobial food packaging. *Innov Food Sci Emerg Technol* **3**:113–126 (2002).
- 232 Han JH, Antimicrobial packaging systems, in *Innovations in Food Packaging*, ed. by Jung HH. Academic Press, London, pp. 80–108 (2005).
- 233 Ünalın IU, Arcan I, Korel F and Yemenicioğlu A, Application of active zein based films with controlled release properties to control *Listeria monocytogenes* growth and lipid oxidation in fresh Kasha cheese. *Innov Food Sci Emerg Technol* **20**:208–214 (2013).
- 234 Kanmani P and Rhim J, Antimicrobial and physical-mechanical properties of agar-based films incorporated with grapefruit seed extract. *Carbohydr Polym* **102**:708–716 (2014).
- 235 Jang S, Shin YJ and Song KB, Effect of rape seed protein gelatin film containing grape fruit seed extract on 'Maehyang's strawberry quality. *Int J Food Sci Technol* **46**:620–625 (2011).
- 236 Vodnar DC, Inhibition of *Listeria monocytogenes* ATCC 19115 on ham steak by tea bioactive compounds incorporated into chitosan-coated plastic films. *Chem Cent J* **6**:1–6 (2012).
- 237 Sabaghia M, Maghsoudloua Y, Khomeiria M and Ziaifarab AM, Active edible coating from chitosan incorporating green tea extract as an antioxidant and antifungal on fresh walnut kernel. *Postharvest Biol Technol* **110**:224–228 (2015).
- 238 Nerin C, Tovar L, Djenane D, Camo J, Salafranca J, Beltrán JA *et al.*, Stabilization of beef meat by a new active packaging containing natural antioxidants. *J Agric Food Chem* **54**:7840–7846 (2006).
- 239 Camo J, Lores A, Djenane D, Beltrán JA and Roncales P, Display life of beef packaged with an antioxidant active film as a function of the concentration of oregano extract. *Meat Sci* **88**:174–178 (2011).
- 240 Commission Regulation (EC) No. 450/2009 of 29 May 2009 on active and intelligent materials and articles intended to come into contact with food. *Official J Eur Union*. L 135/3.
- 241 Gherardi R, Becerril R, Nerin C and Bosetti O, Development of a multilayer antimicrobial packaging material for tomato puree using an innovative technology. *LWT Food Sci Technol* **72**:361–367 (2016).
- 242 Vermeiren LDF and Debevere J, Effectiveness of some recent antimicrobial packaging concepts. *Food Addit Contam* **19**:163–171 (2002).
- 243 Gutierrez L, Batlle R, Sanchez C and Nerin C, New approach to study the mechanism of antimicrobial protection of an active packaging. *Foodborne Pathog Dis* **7**:1063–1069 (2010).
- 244 Cooksey K, Effectiveness of antimicrobial food packaging materials. *Food Addit Contam* **22**:980–987 (2005).
- 245 Colon M and Nerin C, Development and application of an analytical procedure for specific migration of green tea compounds in IV gamma nectarine active packaging. *Food Control* **57**:419–425 (2015).
- 246 Han C, Wang J, Li Y, Lub F and Cui Y, Antimicrobial-coated polypropylene films with polyvinyl alcohol in packaging of fresh beef. *Meat Sci* **96**:901–907 (2014).
- 247 Calatayud M, López-de-Dicastillo C, López-Carballo G, Vélez D, Hernández Muñoz P and Gavara R, Active films based on cocoa extract with antioxidant, antimicrobial and biological applications. *Food Chem* **139**:51–58 (2013).
- 248 Takala PN, Salmieri S, Boumail A, Khan RA, Vu KD, Chauve G *et al.*, Antimicrobial effect and physico-chemical properties of bioactive tri-layer polycaprolactone/methylcellulose-based films on the growth of foodborne pathogens and total microbiota in fresh broccoli. *J Food Eng* **116**:648–655 (2013).