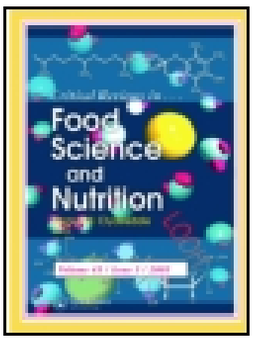

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# Plant extracts rich in polyphenols: antibacterial agents and natural preservatives for meat and meat products

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REVIEW



# Plant extracts rich in polyphenols: antibacterial agents and natural preservatives for meat and meat products

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**ABSTRACT**

Plant extracts contain large amounts of bioactive compounds, mainly polyphenols. Polyphenols inhibit the growth of microorganisms, especially bacteria. Their mechanism of action is still not fully understood but may be related to their chemical structure. They can cause morphological changes in microorganisms, damage bacterial cell walls and influence biofilm formation. Polyphenols also influence protein biosynthesis, change metabolic processes in bacteria cells and inhibit ATP and DNA synthesis (suppressing DNA gyrase). Due to the antioxidant and antibacterial activity of phenolic compounds, plant extracts offer an alternative to chemical preservatives used in the meat industry, especially nitrates (III). They can inhibit the growth of spoilage and pathogenic microflora, suppress oxidation of meat ingredients (lipids and proteins) and prevent discoloration. In this paper, we describe the factors that influence the content of polyphenols in plants and plant extracts. We present the antimicrobial activities of plant extracts and their mechanisms of action, and discuss the effects of plant extracts on the shelf-life of meat and meat products.

**KEYWORDS**

Polyphenols; plant extracts; antibacterial activity; meat

## Introduction

According to Regulation (EC) No. 1333/2008 of the European Parliament and of the Council of 16 December 2008 on food additives, "preservatives are substances which prolong the shelf-life of foods by protecting them against deterioration caused by micro-organisms and/or which protect against growth of pathogenic micro-organisms." Microbial processes can lead to unfavorable changes in food quality and may be dangerous to human health. Meat, due to its high water activity, high content of nutritional ingredients and pH = 5.5–6.5, is a good environment for the growth of microorganisms, mainly bacteria. Microorganisms often detect in meat and meat products include *Brochothrix thermosphacta, Carnobacterium* sp., *Leuconostoc* sp., *Lactococcus* sp., *Lactobacillus* sp., *Pseudomonas* sp., *Enterococcus* sp., *Enterobacter* sp., *Acinetobacter* sp., *Moraxella* sp., *Aeromonas* sp., *Psychrobacter* sp., *Serratia* sp. and *Enterobacteriaceae* (Dolan et al. 2009; Stoops et al. 2015; Pennacchia, Ercolini, and Villani 2011).

Chemical preservatives are therefore of great importance to the meat industry. The most commonly used meat preservatives are nitrates (III): potassium nitrate (IIII) (E249) and sodium nitrate (III) (E250). These are used in mixtures with salt or salt substitute. Nitrates (III) extend the shelf life of meat products by inhibiting the growth of spoilage and pathogenic bacteria (including *Clostridium botulinum*) and reducing the oxidation of meat ingredients. Moreover, they improve the organoleptic properties of meat and impart a characteristic pink-red color. Due to their inhibitory activity against pathogenic bacteria, especially *C. botulinum*, the use of nitrates (III) is required in the meat industry. However, they can be harmful to human health. The near acidic pH of meat products and heating processes ($t > 130\,^{\circ}C$) such as frying or grilling enable the interaction of nitrates (III) with amino compounds, such as proteins, amino acids or amines. As a result, carcinogenic N-nitrosamines are released. Moreover, nitrates (III) increase the formation of methemoglobin, which is unable to transport oxygen. As a consequence, there is a risk of methemoglobinemia. Nitrates (V), sodium nitrate (V) (E251) and potassium nitrate (V) (E252) are also permitted for use in meat processing but are inert compounds. In the meat environment, they are reduced to highly active nitrates (III) by naturally occurring bacteria or bacteria that have been added, such as *Staphylococcus* sp., *Micrococcus* sp. or lactic acid bacteria, which show nitrate reductase activity. The maximum acceptable level of nitrates (III) or nitrates (V) is 150 mg/kg (Cantwell and Elliott 2017; Alahakoon et al. 2015; Govari and Pexara 2015).

Other preservatives, in addition to nitrates, are available for use in the meat industry. These include sulfur dioxide-sulphates (IV) (E220–228), acetic acid (E260), potassium acetate (E261) and sodium acetate (E262), calcium acetate (E263), sorbic acid - sorbates (E200–203), benzoic acid - benzoates (E210–213), p-hydroxybenzoates (E214-219), natamycin (E235) and lactic acid (E270). Lactic acid, acetic acid and acetates are generally considered to be harmless. When used at appropriate doses, other preservatives should also

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not be detrimental to human health. However, their safety is questionable, as they may be linked to hypersensitivity, asthma, cancer, skin irritation, allergies or gastrointestinal problems (Nair 2001; Silva and Lidon 2016)

The use of preservatives depends on the meat category and product and is described in Regulation (EC) No 1333/2008 of the European Parliament and of the Council of 16 December 2008 on food additives, Commission regulation (EU) No. 1129/2011 of 11 November 2011 amending Annex II to Regulation (EC) No 1333/2008 of the European Parliament and of the Council by establishing a Union list of food additives, Commission regulation (EU) 2015/647 of 24 April 2015 amending and correcting Annexes II and III to Regulation (EC) No. 1333/2008 of the European Parliament and of the Council as regards the use of certain food additives and Commission regulation (EU) No. 601/2014 of 4 June 2014 amending Annex II to Regulation (EC) No. 1333/2008 of the European Parliament and of the Council as regards the food categories of meat and the use of certain food additives in meat preparations.

In order to limit the use of chemical preservatives in meat and meat products, especially nitrates (III), new natural preservation methods are needed. The antimicrobial activity of natural products has been widely discussed in the literature. Natural antimicrobial agents can be of plant origin (polyphenols, saponins, iridoids, essential oils), microbial origin (bacteriocins (nisin reuterin, pediocin) or animal origin (peptides (pleurocidin, defensins, lactoferin), chitosan, lysozyme, lipids). Algae are sources of fatty acids, steroids, polyphenols and terpenoid compounds. Mushrooms contain fatty acids, polyphenols, lycopene and polysaccharides (Tiwari et al. 2009; Gyawali and Ibrahim 2014). Although there are many sources of antimicrobial compounds of natural origin, the greatest interest for meat processing is focused on using plant extracts rich in polyphenols.

Polyphenols are secondary plant metabolites which occur throughout plants, in the fruits, flowers, seeds, shells, leaves, roots and even woody parts. These organic compounds differ in terms of their structure and molecular weight, as well as in their chemical, physical and biological properties. They are composed of at least one aromatic ring, to which at least two hydroxyl groups are attached. They may also exist in the form of esters or glycosides. According to differences in their structure, polyphenolic compounds are divided into four groups: phenolic acids, flavonoids, stilbenes and lignans. Table 1 presents the polyphenolic compounds in several plants.

Polyphenols are known for their strong antioxidant properties. Their activity is based on scavenging free radicals and reactive oxygen/nitrogen species, the reduction of oxidized intermediates, metals binding (mainly iron and copper), the inhibition of enzymes responsible for the formation of free radicals (oxidase, peroxidase), the activation of antioxidant enzymes (catalase, superoxide dismutase) and the prevention of oxidation of other antioxidants (ascorbic acid, vitamin E). Due to the antioxidant properties of polyphenols, these compounds can play an important role in cancer prevention and therapy. Moreover, polyphenolic compounds have many other beneficial effects on human health, including anti-inflammatory, antidiabetic, antiallergic, antiatherogenic, antihypertensive, antithrombotic, anticancer, cardioprotective, osteoprotective, neuroprotective, antiaging and hepatoprotective properties (Pandey and Rizvi 2009; Gorzynik-Debicka et al. 2018). The antibacterial, antitoxin, antiviral and antifungal properties of polyphenols have been also documented (Friedman 2007; Daglia 2012).

Despite their many health benefits, there are some hazards related to consumption of polyphenols. The toxicity of polyphenols is strictly related to the dose. Depending on the concentration, polyphenols can show both toxic and non-toxic activity. Polyphenols can have carcinogenic/genotoxic effects and may interfere with thyroid hormone biosynthesis. They also have estrogenic activity, which can cause both detrimental and beneficial effects, and show antinutritional effects (iron depletion). They can also interact with certain pharmaceuticals. However, the risk of these toxic effects is very low (Mennen et al. 2005; Cory et al. 2018).

Due to the antioxidant and antimicrobial properties of polyphenols, their use as natural preservatives in meat and meat products is of great interest currently. Plant extracts rich in polyphenols can extend the shelf life of meat and meat products, by inhibiting the growth of spoilage and pathogenic microflora, inhibiting the oxidation of meat products and preventing discoloration and organoleptic changes (Papuc et al. 2017; Karre, Lopez, and Getty 2013). This review presents factors influencing the content of polyphenols in plants and plant extracts. The antimicrobial activity of plant extracts and their mechanisms of action are described. Finally, their effects on the shelf life of meat and meat products are discussed.

## Differentiation of phenolic content and antioxidant activity in plants and plant extracts

The content of polyphenolic compounds in plants varies widely. There are many factors that influence the composition and concentration of polyphenols, as well as the antioxidant capacity of plants and plant extracts, such as the organ, cultivar and growth season. In their study of black currants, Tabart et al. (2006) report that the TPC was the highest in the leaves (>150 $mg_{CAE}$/g of DW), followed by the flowers (approximately 100 $mg_{CAE}$/g of DW), buds (>50 $mg_{CAE}$/g of DW) berries (approximately 50 $mg_{CAE}$/g of DW), apex (approximately 40 mg $_{CAE}$/g of DW) and bases(approximately 20 $mg_{CAE}$/g of DW). Antioxidant activity was the strongest in the buds and berries (approximately 50 $mg_{TE}$/g of DW), followed by the apex (approximately 30 $mg_{TE}$/g of DW), flowers (approximately 30 $mg_{TE}$/g of DW), leaves (approximately 20 $mg_{TE}$/g of DW) and bases (approximately 10 $mg_{TE}$/g of DW). Interestingly, the TPC and antioxidant activity decreased from the apex to the base of the stem. Vagiri et al. (2012) also found that black currant leaves (89–97 $mg_{GA}$/g of DW) contained more phenolic compounds than the buds (45–56 $mg_{GA}$/g of DW).

Teleszko and Wojdyło (2015) analyzed seven selected species of plants (apple, quince, Japanese quince, chokeberry,

**Table 1.** Polyphenolic compounds in different plants.

| Plant | Scientific name | Part of plant | Group of polyphenols | Polyphenolic compounds | Reference |
|---|---|---|---|---|---|
| Black currant | *Ribes nigrum* l. | Leaves | Hydroxycinnamic acid derivatives | p-coumaric acid, o-coumaric acid, caffeic acid, chlorogenic acid | Chrzanowski et al. (2012) |
| | | | Hydroxybenzoic acid derivatives | Benzoic acid, p-hydroxybenzoic acid, vanillic acid, syringic acid, | |
| Black currant | *Ribes nigrum* L. | Leaves | Hydroxycinnamic acid derivatives | Neochlorogenic acid, chlorogenic acid, caffeic acid derivative | Nowak et al. (2016) |
| | | | Hydroxybenzoic acid derivatives | Gallic acid, syryngic acid, syringin glucoside | |
| | | | Flavan-3-ols | EGC | |
| Black currant | *Ribes nigrum* l. | Leaves, fruits | Flavonols | Quercetin glycoside, kaempferol glucoside, kaempferol galactoside, kaempferol rutinoside | Teleszko and Wojdyło (2015) |
| | | | Flavonols | Myricetin-3-O-rutinoside, myricetin-3-O-galactoside, quercetin-3-O-galactoside, quercetin-3-O-rutinoside, quercetin-3-O-glucoside, kaempferol-3-O-galactoside, kaempferol-3-O-rutinoside, kaempferol-3-O-glucoside | |
| Black currant | *Ribes nigrum* l. | Leaves, buds, fruits | Hydroxycinnamic acid derivatives | Chlorogenic acid, neochlorogenic acid | Vagiri et al. (2012) |
| | | | Flavan-3-ols | Catechin, EC, EGC | |
| | | | Flavonols | Myricetin malonyl-glucoside, quercetin-3-O-glucoside, quercetin-3-O-galactoside, quercetin-3-O-rutinoside, quercetin-3-6-malonyl-glucoside, kaempferol-3-O-rutinoside, kaempferol-3-O-glucoside, kaempferol malonyl-glucoside, kaempferol malonyl-glucoside isomer, isorhamnetin-3-O-rutinoside, isorhamentin-3-O-glucoside, quercetin aglycone | |
| | | | Anthocyanins | Delphinidin-3-O-glucoside, delphinidin-3-O-rutinoside, cyanidin-3-O-glucoside, cyanidin-3-O-rutinoside | |
| Apple | *Malus domestica* Borkh. | Leaves, fruits | Hydroxycinnamic acid derivatives | Neochlorogenic acid, p-coumaric-quinic acid, chlorogenic acid, cryptochlorogenic acid | Teleszko and Wojdyło (2015) |
| | | | Flavan-3-ols | Catechin, procyanidin B1, EC, procyanidin B2, procyanidin C1 | |
| | | | Flavonols | Quercetin-3-O-galactoside, quercetin-3-O-rutinoside, quercetin-3-O-glucoside, quercetin-3-O-rhamnoside | |
| | | | Dihydrochalcones | Phloretin-2′xylo-glucoside, phloridzin | |
| Quince | *Cydonia oblonga* Mill. | Leaves, fruits | Hydroxycinnamic acid derivatives | Neochlorogenic acid, chlorogenic acid, cryptochlorogenic acid, unknown chlorogenic acid isomer, 5-O-feruloylquinic acid, 3,5-O-dicaffeoyloquinic acid | Teleszko and Wojdyło (2015) |
| | | | Flavan-3-ols | Catechin, procyanidin B1, EC, procyanidin B2, procyanidin C1 | |
| | | | Flavonols | Quercetin-3-O-galactoside, quercetin-3-O-rutinoside, quercetin-3-O-glucoside, kaempferol-3-O-galactoside, kaempferol-3-O-rutinoside, kaempferol-3-O-glucoside | |
| Japanese quince | *Chaenomeles japonica* l. | Leaves, fruits | Hydroxycinnamic acid derivatives | Chlorogenic acid | Teleszko and Wojdyło (2015) |
| | | | Flavan-3-ols | Procyanidin B3, catechin, procyanidin B1, EC, procyanidin B2, procyanidin C1 | |
| | | | Flavonols | Quercetin-3-O-galactoside, quercetin-3-O-rutinoside | |
| Chokeberry | *Aronia melanocarpa* (Michx.) Elliott | Leaves | Hydroxycinnamic acid derivatives | Chlorogenic acid isomers, dicaffeoylquinic acid | Lee et al. (2014) |
| | | | Flavonols | Quercetin dirhamnosylhexoside, quercetin rhamnosylhexoside, quercetin 3-O-vicianoside, quercetin 3-O-rutinoside, quercetin 3-O-glucoside, kaempferol coumaroylglucoside, isorhamnetin rhamnosylhexoside isomers | |
| | | | Flavones | Apigenin 7, 4′-di-O-rhamnoside | |
| Chokeberry | *Aronia melanocarpa* (Michx.) Elliott | Leaves | Hydroxycinnamic acid derivatives | Chlorogenic acid, neochlorogenic acid, caffeic acid derivatives, caffeic acid, p-coumaric acid | Skupień et al. (2008) |
| | | | Flavonols | Quercetin, quercetin derivatives | |

(*continued*)

**Table 1.** Continued.

| Plant | Scientific name | Part of plant | Group of polyphenols | Polyphenolic compounds | Reference |
|---|---|---|---|---|---|
| Chokeberry | *Aronia melanocarpa* (Michx.) Elliott | Leaves, fruits | Hydroxycinnamic acid derivatives | Neochlorogenic acid, chlorogenic acid, | Teleszko and Wojdyło (2015) |
| | | | Flavan-3-ols | EC | |
| | | | Flavonols | Quercetin-3-O-vicianoside, quercetin-3-O-robinobioside, quercetin-3-O-galactoside, quercetin-3-O-rutinoside, quercetin-3-O-glucoside | |
| Cranberry | *Vaccinium oxycoccus* | Lruits | Hydroxycinnamic acid derivatives | p-coumaric acid-O-hexoside | Borges et al. (2010) |
| | | | Flavan-3-ols | EC | |
| | | | Flavonols | Myricetin-3-O-galactoside, myricetin-3-O-arabinoside, quercetin-3-O-galactoside, quercetin-3-O-(2″-O-xylosyl)pyranoside, quercetin-3-O-arabinosylpyranoside, quercetin-3-O-arabinosylfuranoside, quercetin-3-O-rhamnoside | |
| | | | Anthocyanins | Cyanidin-3-O-galactoside, cyanidin-3-O-arabinoside, peonidin-3-O-galactoside, peonidin-3-O-glucoside, peonidin-3-O-arabinoside, malvidin-3-O-arabinoside | |
| | | | Proanthocyanidins | Procyanidin dimers | |
| Cranberry | *Vaccinium macrocarpon* l. | Leaves, fruits | Flavan-3-ols | Catechin, procyanidin B1, EC | Teleszko and Wojdyło (2015) |
| | | | Flavonols | Myricetin-3-xylopiranoside, quercetin-3-O-galactoside, quercetin-3-O-rhamnoside, methoxyquercetin-3-O-galactoside, dimethoxymyricetin-hexoside, methoxyquercetin-pentoside | |
| Bilberry | *Vaccinium myrtillus* l. | Leaves, fruits | Hydroxycinnamic acid derivatives | Caffeic acid | Teleszko and Wojdyło (2015) |
| | | | Flavonols | Myricetin-3-O-galactoside, quercetin-3-O-galactoside, | |
| Sour cherry | *Prunus cerasus* L. | Leaves | Hydroxycinnamic acid derivatives | Neochlorogenic acid, chlorogenic acid, coumaric acid | Nowak et al. (2016) |
| | | | Hydroxybenzoic acid derivatives | Gallic acid, protocatechuic acid | |
| | | | Flavan-o-ols | EGC | |
| | | | Flavonols | Quercetin glycoside, kaempferol glucoside | |
| Sour cherry | *Prunus cerasus* l. | eaves | Hydroxycinnamic acid derivatives | Trans-cinnamic, p-coumaric acid, caffeic acid, chlorogenic acid | Chrzanowski et al. (2012) |
| | | | Hydroxybenzoic acid derivatives | Gallic acid, benzoic acid, p-hydroxybenzoic acid, vanillic acid, syringic acid, | |
| Walnut | *Juglans regia* l. | Leaves | Hydroxycinnamic acid derivatives | Trans-cinnamic, p-coumaric acid, o-coumaric acid, caffeic acid, ferulic acid, chlorogenic acid | Chrzanowski et al. (2012) |
| | | | Hydroxybenzoic acid derivatives | Gallic acid, p-hydroxybenzoic acid, vanillic acid, syringic acid | |
| | | | Tanins | Tannic acid | |
| Mulberry | *Morus alba* l. | Leaves | Hydroxycinnamic acid derivatives | Chlorogenic acid, neochlorogenic acid, caffeic acid derivatives, caffeic acid | Skupień et al. (2008) |
| | | | Flavonols | Quercetin, quercetin derivatives, kaempferol | |
| Yerba maté | *Ilex paraguariensis* | Leaves | Hydroxycinnamic acid derivatives | Caffeic acid, quinic acid, caffeoyl glucose, chlorogenic acid, feruloylquinic acid, dicaffeoylquinic acid | Bastos et al. (2007) |
| | | | Flavonols | Quercetin-3-O-rutinoside | |
| Green tea | *Camelia sinensis* | Leaves | Hydroxycinnamic acid derivatives | Quinic acid, caffeoyl glucose, chlorogenic acid, feruloylquinic acid | Bastos et al. (2007) |
| | | | Flavonols | Quercetin-3-O-rutinoside | |
| | | | Flavan-3-ols | Catechin, EC, ECG, methyl-ECG, EGCG, 3-methyl-EGCC | |
| Blueberry | *Vaccinium corymbosum* | Fruits | Hydroxycinnamic acid derivatives | 5-O-feruloylquinic acid | Borges et al. (2010) |
| | | | Flavonols | Quercetin-O-diglucoside, myricetin-3-O-galactoside, quercetin-3-O-rutinoside, quercetin-3-O-galactoside, quercetin-3-O-glucoside, quercetin-3-O-arabinoside, quercetin-3-O-(6″-O-acetyl)glucoside | |
| | | | Anthocyanins | Delphinidin-3-O-galactoside, delphinidin-3-O-glucoside, cyanidin-3-O-galactoside, delphinidin-3-O-arabinoside, cyanidin-3-O-arabinoside, petunidin-3-O-galactoside, petunidin-3-O-arabinoside, | |

(*continued*)

**Table 1.** Continued.

| Plant | Scientific name | Part of plant | Group of polyphenols | Polyphenolic compounds | Reference |
|---|---|---|---|---|---|
| | | | | peonidin-3-O-galactoside, malvidin-3-O-galactoside, malvidin-3-O-glucoside, delphinidin-3-O-(6″-O-acetyl)glucoside, peonidin-3-O-arabinoside, malvidin-3-O-arabinoside, petunidin-3-O-(6″-O-acetyl)glucoside, malvidin-3-O-(6″-O-acetyl)glucoside | |
| Raspberries | *Rubus idaeus* | Fruits | Hydroxycinnamic acid derivatives | Ellagic acid | Borges et al. (2010) |
| | | | Flavonols | Quercetin-O-galactosylrhamnoside, quercetin-3-O-(2″-O-glucosyl)rutinoside, quercetin-3-O-galactoside, quercetin-3-O-glucoside | |
| | | | Anthocyanins | Cyanidin-3-O-sophoroside, cyanidin-3-O-(2″-O-glucosyl)rutinoside, cyanidin-3-O-sambubioside, cyanidin3-O-glucoside, pelargonidin-3-O-sophoroside, cyanidin-3-O-rutinoside, pelargonidin-3-O-glucoside, pelargonidin-3-O-(2″-O-glucosyl)rutinoside | |
| | | | Tanins | Lambertianin c, sanguiin h-6, ellagic acid-O-pentoside, ellagic acid-O-pentoside, ellagic acid-4-O-acetylxyloside | |
| Red currant | *Ribes rubrum* | Fruits | Phenolic acids | 4-hydroxybenzoic acid-O-hexoside, caffeic acid-O-glucoside | Borges et al. (2010) |
| | | | Flavonols | Myricetin-3-O-rutinoside, myricetin-O-rhamnoside, quercetin-3-O- rutinoside, quercetin-3-O- galactoside, quercetin-3-O-glucoside, quercetin-3-O-(6″-O-malonyl)glucoside, kaempferol-O-rutinoside, kaempferol-3-O-galactoside, kaempferol-3-O-glucoside | |
| | | | Anthocyanins | Cyanidin-3-O-sambubioside, cyanidin-3-O-rutinoside, cyanidin-3-O-(2″-O-xylosyl)rutinoside | |
| Grape | *Vitis vinifera* cv. *m. Palieri* (red) | Skin | Flavonols | Myricetin glucoside, quercetin glucuronide, quercetin glucoside, taxifolin deoxyglycoside, isorhamnetin glucoside, syringetin glucoside, isorhamnetin | Cavaliere et al. (2008) |
| | | | Flavan-3-ols | Procyanidin B1, catechin, procyanidin B2, EC | |
| | | | Anthocyanins | Delphinidin-3-O-glucoside, cyanidin-3-O-glucoside, petunidin-3-O-glucoside, peonidin-3-O-glucoside, malvidin-3-O-glucoside, peonidin-3-O-(6-O-acetyl)glucoside, malvidin-3-O-(6-O-acetyl)glucoside, malvidin-3-O-(6-O-caffeoyl)glucoside, cyanidin-3-O-(6-O-coum.)glucoside, delphinidin-3-O-coum glucoside, peonidin-3-O-(6-O-coum.)glucoside, malvidin-3-O-(6-O-coum.)glucoside | |
| | | | Stilbenes | Trans-resveratrol glucoside (piceid), cis-resveratrol, resveratrol tetramers, resveratrol dimers | |
| Grape | *Vitis vinifera* cv. Red Globe (red) | Skin | Flavonols | Myricetin glucoside, quercetin glucuronide, quercetin glucoside, taxifolin deoxyglycoside, isorhamnetin glucoside, syringetin glucoside, isorhamnetin, kaempferol glucoside | Cavaliere et al. (2008) |
| | | | Flavan-3-ols | Procyanidin B1, catechin, procyanidin B2, EC | |
| | | | Anthocyanins | Delphinidin-3-O-glucoside, cyanidin-3-O-glucoside, petunidin-3-O-glucoside, peonidin-3-O-glucoside, malvidin-3-O-glucoside, peonidin-3-O-(6-O-acetyl)glucoside, cyanidin-3-O-(6-O-coum.)glucoside, delphinidin-3-O-coum glucoside, peonidin-3-O-(6-O-coum.)glucoside, malvidin-3-O-(6-O-coum.)glucoside | |
| | | | Stilbenes | Trans-resveratrol glucoside (piceid), cis-resveratrol, resveratrol tetramers, resveratrol dimers | |

(*continued*)

**Table 1.** Continued.

| Plant | Scientific name | Part of plant | Group of polyphenols | Polyphenolic compounds | Reference |
|---|---|---|---|---|---|
| Grape | *Vvitis vinifera* cv.Italia (white) | Skin | Flavan-3-ols | Procyanidin B1, catechin, procyanidin B2, EC, other dimers, trimers and tetramers | Cavaliere et al. (2008) |
| | | | Flavonols | Quercetin glucuronide, quercetin glucoside, taxifolin deoxyglycoside, isorhamnetin glucoside | |
| Grape | *Vitis vinifera* cv. m. Palieri (red) | Seeds | Flavan-3-ols | Procyanidin B1, catechin, procyanidin B2, EC, ECG, CG, other procyanidin dimers, procyanidin gallate, procyanidin trimers, procyanidin trimers gallate, procyanidin tetramers | Cavaliere et al. (2008) |
| Grape | *Vitis vinifera* cv. Red Globe (red) | Seeds | Flavan-3-ols | Procyanidin B1, catechin, procyanidin B2, EC, ECG, CG, other procyanidin dimers, procyanidin gallate, procyanidin trimers, procyanidin trimers gallate, procyanidin tetramers | Cavaliere et al. (2008) |
| Grape | *Vitis vinifera* cv.Italia (white) | Seeds | Flavan-3-ols | Procyanidin B1, catechin, procyanidin B2, EC, ECG, CG, other procyanidin dimers, procyanidin gallate, procyanidin trimers, procyanidin trimers gallate, procyanidin tetramers | Cavaliere et al. (2008) |
| Rosemary | *Rosmarinus officinalis* | Leaves | Hydroxycinnamic acid derivatives | Caffeic acid-O-hexosides, neochlorogenic acid, protocatechuic acid, caffeic acid-O-hexosides, chlorogenic acid, coumaric acid-O-hexoside, cryptochlorogenic acid, caffeic acid, 4-O-p-coumaroylqunic acid, ferulic acid-O-hexoside, sinapic acid-c-hexoside, coumaric acid, rosmarinic acid-O-hexoside, ferulic acid, dicaffeoylquinic acid, rosmarinic acid | Vallverdú-Queralt et al. (2014) |
| | | | Hydroxybenzoic acid derivatives | Gallic acid, vanillic acid-O-hexoside, syringic acid, homovanillic acid-O-hexoside, p-hydroxybenzoic acid, m-hydroxybenzoic acid | |
| | | | Flavones | Apigenin-c-hexoside-c-hexoside, apigenin-7-O-glucoside, apigenin, | |
| | | | Flavonols | Quercetin-3-O-rutinoside, kaempferol-3-O-rutinoside, quercetin-3-O-glucoside, kaempferol-3-O-glucoside, kaempferol, quercetin | |
| | | | Flavanones | Naringenin-c-hexoside, hesperidin, hesperetin | |
| | | | Phenolic terpenes | Carnosol, rosmanol, carnosic acid | |
| thyme | *Thymus vulgaris* | Leaves | Hydroxycinnamic acid derivatives | Caffeic acid-O-hexosides, neochlorogenic acid, protocatechuic acid, caffeic acid-O-hexosides, chlorogenic acid, coumaric acid-O-hexoside, cryptochlorogenic acid, caffeic acid, 4-O-p-coumaroylqunic acid, ferulic acid-O-hexoside, sinapic acid-c-hexoside, coumaric acid, ferulic acid, dicaffeoylquinic acid, | Vallverdú-Queralt et al. (2014) |
| | | | Hydroxybenzoic acid derivatives | Gallic acid, vanillic acid-O-hexoside, syringic acid, homovanillic acid-O-hexoside, p-hydroxybenzoic acid, m-hydroxybenzoic acid, homovanillic acid, vanillic acid, | |
| | | | Flavones | Apigenin-7-O-glucoside, apigenin, | |
| | | | Flavonols | Quercetin-3-O-rutinoside, kaempferol-3-O-rutinoside, quercetin-3-O-glucoside, kaempferol-3-O-glucoside, kaempferol, quercetin | |
| | | | Flavanones | Naringenin-c-hexoside, hesperidin, hesperetin | |
| | | | Phenolic terpenes | Carnosic acid | |
| Oregano | *Origanum vulgare* | Leaves | Hydroxycinnamic acid derivatives | Caffeic acid-O-hexosides, neochlorogenic acid, protocatechuic acid, caffeic acid-O-hexosides, chlorogenic acid, coumaric acid-O-hexoside, cryptochlorogenic acid, caffeic acid, 4-O-p-coumaroylqunic acid, coumaric acid, rosmarinic acid-O-hexoside, ferulic acid, dicaffeoylquinic acid | Vallverdú-Queralt et al. (2014) |
| | | | Hydroxybenzoic acid derivatives | Gallic acid, vanillic acid-O-hexoside, syringic acid, p-hydroxybenzoic acid, m-hydroxybenzoic acid, homovanillic acid, | |

(*continued*)

**Table 1.** Continued.

| Plant | Scientific name | Part of plant | Group of polyphenols | Polyphenolic compounds | Reference |
|---|---|---|---|---|---|
| | | | Flavones | Apigenin-c-hexoside-c-hexoside, apigenin-7-O-glucoside, apigenin, | |
| | | | Flavonols | Kaempferol-O-dihexoside, kaempferol-3-O-rutinoside, quercetin-3-O-glucoside, kaempferol-3-O-glucoside, kaempferol, quercetin | |
| | | | Flavanones | Hesperidin, hesperetin | |
| | | | Phenolic terpenes | Carnosol, rosmanol, carnosic acid | |
| Cumin | *Cuminum cyminum* | Fruits | Hydroxycinnamic acid derivatives | Caffeic acid-O-hexoside, neochlorogenic acid, caffeic acid-O-hexosides, 3-O-p-coumaroylqunic acid, chlorogenic acid, cryptochlorogenic acid, caffeic acid, 4-O-p-coumaroylqunic acid, coumaric acid, ferulic acid, dicaffeoylquinic acid | Vallverdú-Queralt et al. (2014) |
| | | | Hydroxybenzoic acid derivatives | Gallic acid, syringic acid, protocatechuic acid, p-hydroxybenzoic acid, m-hydroxybenzoic acid, | |
| | | | Flavan-3-ols | Catechin, EC | |
| | | | Proanthocyanidins | Proanthocyanidin trimers, proanthocyanidin hexamer | |
| | | | Flavonols | Quercetin-3-O-rutinoside, kaempferol-3-O-rutinoside, quercetin-3-O-glucoside, kaempferol-3-O-glucoside, kaempferol, quercetin | |
| | | | Flavanones | Naringenin-O-hexuronide, hesperetin | |
| | | | Phenolic terpenes | Rosmarinic acid | |
| Cinnamon | *Cinnamomum zeylanicum* | bark | Hydroxycinnamic acid derivatives | Caffeic acid-O-hexosides, neochlorogenic acid, chlorogenic acid, cryptochlorogenic acid, caffeic acid, 4-O-p-coumaroylqunic acid, ferulic acid-O-hexoside, coumaric acid, ferulic acid, dicaffeoylquinic acid, rosmarinic acid | Vallverdú-Queralt et al. (2014) |
| | | | Hydroxybenzoic acid derivatives | Gallic acid, syringic acid, protocatechuic acid, homovanillic acid-O-hexoside, p-hydroxybenzoic acid, m-hydroxybenzoic acid, | |
| | | | Flavan-3-ols | Catechin | |
| | | | Proanthocyanidins | Proanthocyanidin trimers, proanthocyanidin hexamer | |
| | | | Flavonols | Quercetin-3-O-rutinoside, quercetin-3-O-glucoside, kaempferol-3-O-glucoside, kaempferol, quercetin, | |
| | | | Flavanones | Naringenin-c-hexoside | |
| | | | Flavones | Apigenin | |
| | | | Phenolic terpenes | Carnosic acid | |
| Bay | *Laurus nobilis* | Leaves | Hydroxycinnamic acid derivatives | Caffeic acid-O-hexosides, neochlorogenic acid, chlorogenic acid, coumaric acid-O-hexoside, cryptochlorogenic acid, caffeic acid, 4-O-p-coumaroylqunic acid, coumaric acid-O-hexoside, coumaric acid, ferulic acid, rosmarinic acid | Vallverdú-Queralt et al. (2014) |
| | | | Hydroxybenzoic acid derivatives | Gallic acid, vanillic acid-O-hexoside, syringic acid, protocatechuic acid, homovanillic acid-O-hexoside, p-hydroxybenzoic acid, m-hydroxybenzoic acid, homovanillic acid, vanillic acid, | |
| | | | Flavonols | Quercetin-3-O-rutinoside, kaempferol-3-O-rutinoside, kaempferol-3-O-glucoside, kaempferol, quercetin | |
| | | | Flavanones | Naringenin, hesperetin | |
| Saskatoon | *Amelanchier alnifolia* nutt. | Fruits | Hydroxycinnamic acid derivatives | Neochlorogenic acid, chlorogenic acid, hydroxycinnamic acid derivatives | Lavola, Karjalainen, and Julkunen-Tiitto (2012) |
| | | | Hydroxybenzoic acid derivatives | Protocatechuic acid | |
| | | | Anthocyanins | Cyanidin 3-galactoside, cyanidin 3-glucoside, cyanidin 3-arabinoside, cyanidin 3-xyloside | |
| | | | Flavonols | Quercetin arabinoglucoside, quercetin 3-galactoside, quercetin glycoside, quercetin 3-glucoside, quercetin 3-rutinoside, quercetin 3-arabinoside, quercetin 3-xyloside, monocoumaroyl-isoquercetin | |

(*continued*)

**Table 1.** Continued.

| Plant | Scientific name | Part of plant | Group of polyphenols | Polyphenolic compounds | Reference |
|---|---|---|---|---|---|
| | | | Flavan-3-ols | Catechin derivatives, procyanidin derivatives | |
| Saskatoon | *Amelanchier alnifolia* nutt. | Leaves | Hydroxycinnamic acid derivatives | Neochlorogenic acid, chlorogenic acid, hydroxycinnamic acid derivatives | Lavola, Karjalainen, and Julkunen-Tiitto (2012) |
| | | | Hydroxybenzoic acid derivatives | Protocatechuic acid | |
| | | | Flavonols | Quercetin 3-galactoside, quercetin 3-glucoside, quercetin 3-arabinoside, quercetin 3-xyloside, quercetin diarabinoglucuronide, quercetin arabinoglucuronide, quercetin arabinoglucoside, quercetin glycoside, quercetin diglycoside, kaempferol 3-glucoside, kaempferol derivatives, monocoumaroyl-isoquercetin | |
| | | | Flavan-3-ols | Catechin derivative, (-)-EC | |
| | | | p-hydroxyacetophenone | Picein | |
| | | | Lignans | Neolignans | |
| Saskatoon | *Amelanchier alnifolia* nutt. | Stems | Hydroxybenzoic acid derivatives | Protocatechuic acid, protocatechuic acid derivative, benzoic acid, benzoic acid derivative | Lavola, Karjalainen, and Julkunen-Tiitto (2012) |
| | | | lavonols | Quercetin 3-galactoside, quercetin 3-glucoside, quercetin 3-arabinoside, quercetin 3-xyloside, quercetin arabinoglucuronide, quercetin glycoside, quercetin arabinoglucoside, isorhamnetin, isorhamnetin derivative | |
| | | | Flavanones | Eriodictyol, eriodictyol 7-glucoside | |
| | | | Flavan-3-ols | (+)-catechin, catechin derivative, (−)-EC | |
| | | | Proanthocyanidins | Proanthocyanidin derivative, neolignan | |
| | | | p-hydroxyacetophenone | Picein | |
| Schisandra | *Schisandra chinensis* | Fruits | Hydroxycinnamic acid derivatives | Chlorogenic acid, p-coumaric acid, | Mocan et al. (2014) |
| | | | Hydroxybenzoic acid derivatives | Gentisic acid | |
| | | | flavonols | Quercetin 3-O-galactoside, isoquercitrin, quercetin-3-O-rutinoside, quercetin | |
| Schisandra | *Schisandra chinensis* | Leaves | Hydroxycinnamic acid derivatives | Caffeic acid, chlorogenic acid, p-coumaric, ferulic acid | Mocan et al. (2014) |
| | | | Hydroxybenzoic acid derivatives | Gentisic acid | |
| | | | Flavonols | Quercetin 3-O-galactoside, quercetin-3-Orutinosideisoquercitrin, myricetin, quercetin 3-rhamnoside (quercitrin), quercetin, kaempferol | |
| Olive | *Olea europaea* l. | Leaves | Hydroxycinnamic acid derivatives | Caffeic acid, verbascoside | Pereira, Ferreira, et al. (2007) |
| | | | Flavonols | Quercetin-3-O-rutinoside | |
| | | | flavones | Luteolin 7-O-glucoside, luteolin 4′-O-glucoside, apigenin 7-O-glucoside, | |

cranberry, black currant, bilberry). Again, the leaves contained significantly higher amounts of polyphenols compared to the fruits, but no difference was observed in terms of polyphenolic composition. The only exception was Japanese quince (the fruits contained 10% more polyphenols than the leaves). In terms of antioxidant capacity, the trend was similar, except for chokeberry leaves which showed slightly lower antioxidant activity than the fruits. Several parts of plants do not differ in their qualitative composition but only in the concentration of individual compounds. In a study of Tunisian azarole, Belkhir et al. (2013) found the highest content of polyphenols in the leaves (152.38 mg/100 g of FW), followed by the fruit peel (142.46 mg/100 g of FW). The lowest TPC was found in the fruit pulp (26.31 mg/100 g of FW). Differences in the composition of the extracts were also observed. Isoquercitrin was the main compound in the leaves (44.9%), while hyperoside (72.01%) and epicatechin (68.41%) were predominant in the fruit peel and pulp parts, respectively. A strong correlation was observed between the TPC and antioxidant capacity ($R^2 = 0.912$).

Lavola, Karjalainen, and Julkunen-Tiitto (2012) found differences in the polyphenolic composition of the leaves, stems and berries of Saskatoon cultivars. In the berries, the predominant polyphenols were cyanidin-based anthocyanins (63%), quercetin-glycosides and hydroxycinnamic acids. The main components in the leaves were quercetin- and kaempferol-glycosides (41%), hydroxycinnamic acids (36%), catechins and some neolignans. The stems consisted mainly of flavanone and flavonol glycosides (55%), catechins (38%) and hydroxybenzoic acids. High concentrations of proanthocyanidins were detected in the leaves and stems (10 − 14%

of dry biomass). The levels of proanthocyanidins were significantly lower (3% of dry biomass) in the berries.

Mocan et al. (2014) investigated the polyphenolic composition of *Schisandra chinensis* leaves and fruits. The fruits were found to be a poor source of polyphenols in comparison to the leaves. Isoquercitrin was predominant in the leaves (2.49 mg/g of plant material), followed by quercitrin (64 mg/g of plant material). In the fruits, the main flavonoid was rutin (0.013 mg/g plant material), although its concentration was very low. The antioxidant capacity of the leaf and fruit extracts was evaluated using DPPH, TEAC, hemoglobin ascorbate peroxidase activity inhibition (HAPX), inhibition of lipid peroxidation catalyzed by cytochrome c and EPR spectroscopic assays. The results obtained by these five methods showed a good correlation. The leaf extract exhibited stronger antioxidant activity than the fruit extract.

The amounts of polyphenols in plants also differ depending on the growth season. In a study by Tabart et al. (2006), black currant buds, leaves and berries were collected during 2004 and both the TPC and the antioxidant capacity were determined. No significant differences in the levels of phenolics were detected in buds collected from March to October (approximately 60–100 $mg_{CAE}$/g of DW). However, an increase was later observed, with the highest TPC reported in January (approximately 300 $mg_{CAE}$/g of DW). Antioxidant capacity was higher in April and November, which does not correspond with the level of phenolics. In the leaves, TPC (approximately 200 $mg_{CAE}$/g of DW) and antioxidant activity (50 $mg_{TE}$/g of DW) were the highest in June, when the leaves were fully developed and their numbers per branch were highest. In the berries, TPC increased during growth and stabilized during ripening, achieving a maximal level from June to July. Antioxidant capacity was the highest in July, when the fruits were ripe and their weight was greatest. Nour, Trandafir, and Cosmulescu (2014) similarly recorded the highest TPC on 15 June for five out of six investigated cultivars of black currant leaves. Later, a decrease was observed and on 1 August TPC was 45.8–71.1% of the previously recorded level. A similar trend was observed for antioxidant activity. On 15 June, antioxidant activity was approximately 2.9 times higher than on 1 June and 2.5 times higher than on 1 August.

According to Sreelatha and Padma (2009), mature *Moringa oleifera* leaves (48.51 $mg_{GAE}$/g of extract) show higher polyphenolic content TPC than tender leaves (36.02 $mg_{GAE}$/g of extract). However, the differences in antioxidant capacity are not very significant. Both mature and tender leaves show strong radical scavenging activity, prevent oxidative damage to major biomolecules (e.g. DNA) and protect against oxidative damage. Do Thi and Hwang (2014) studied the content of bioactive compounds and antioxidant capacity in the case of extracts obtained from young (2 months old) and old (4 months old) chokeberry leaves. The young leaves (water extract: 141.6 mg/g of DW; 80% ethanol extract: 250.8 mg/g of DW) contained more phenolics than the old leaves (water extract: 69.5 mg/g of DW; 80% ethanol extract: 139.3 mg/g of DW). Differences in antioxidant capacity were also detected. Water extract and 80% ethanol extract from the young leaves respectively caused 28.5% and 64.4% inhibition of DPPH radicals and 20.1% or 35.9% inhibition of ABTS radicals. For water extract and 80% ethanol extract from old leaves, respectively, inhibition of the DPPH radical was 14.6% and 35.3%, while ABTS radical scavenging activity was 9.5% or 23.4%.

Plant cultivar is an important factor affecting the level and composition of phenolics, as well as antioxidant capacity (Tabart et al. 2006; Wojdyło, Oszmiański, and Bielicki 2013). In one study, although different black currant leaf cultivars were found to have identical qualitative compositions the concentrations of individual polyphenols differed significantly (Nour, Trandafir, and Cosmulescu 2014). Nevertheless, p-coumaric and gallic acid were the major polyphenolic compounds in all the tested cultivars, whereas quercetin, myricetin and rutin were the most abundant flavonoids. Moreover, despite differences between the cultivars, the patterns of variation during the harvesting period were similar.

Vrhovsek et al. (2004) report that TPC in different apple varieties ranged from 66.2 to 211.9 mg ((+)catechin)/100 g FW. Flavan-3-ols were the predominant group of polyphenols in all the samples and represented 71–90% of total content of polyphenols. In red apples, hydroxycinnamic acid derivatives composed 4–18% of total polyphenols, followed by flavonols (1–11% of total polyphenols), dihydrochalkones (2–6% of total polyphenols) and finally anthocyanins (1–3% of total polyphenols). Flavan-3-ols were the most abundant in Granny Smith apples, hydroxycinnamates in Fuji, flavonols in Braeburn, dihydrochalkones in Renetta and anthocyanins in Morgenduft and Red Delicious.

Another important factor which influences the phenolic content and antioxidant capacity of plant extracts is the method of extraction. Several organic solvents, such as ethanol, methanol, acetone and chloroform solutions, are commonly used to isolate bioactive compounds, although water-inorganic solvent can also be applied. Extraction efficiency differs depending on solvent composition, duration and temperature. Ghasemzadeh, Jaafar, and Rahmat (2011) report that extraction with methanol gives higher TPC, total flavonoid content and stronger antioxidant capacity measured by the DPPH method, compared to chloroform and acetone. Similar results were observed for some individual flavonoids, such as quercetin, catechin and rutin. In addition, an increase in solvent polarity from methanol to chloroform resulted in a higher level of phenolics and increased antioxidant activity. Lapornik, Rošek, and Wondra (2005) demonstrated that ethanol and methanol extracts obtained from red and black currant contain twice as many anthocyanins and phenolic compounds as water extracts. The values for grape marc extracts were seven times higher than for water extracts. The antioxidant capacity of ethanol with methanol grape extracts was several times higher than that of water extract. However, black and red currant extracts prepared using three types of solvents did not show significant differences in terms of antioxidant activity.

It should be emphasized that phenolic compounds show different polarities. Mixtures of water and organic solvent seem to

be the most suitable systems for isolating a wide range of antioxidants (Dent et al. 2013; Durling et al. 2007). Dent et al. (2013) investigated the effect of extraction solvents (30, 50 and 70% aqueous solutions of ethanol with acetone and 100% distilled water), temperature (60 and 90 °C) and extraction time (30, 60 or 90 min) on the phenolic content in Dalmatian wild sage (*Salvia officinalis* L.). Binary-solvent systems were found to be more efficient than mono-solvent systems. Moreover, the highest extraction efficiency was observed using aqueous solutions of ethanol or acetone (30%) at 60 °C for 30 min.

Durling et al. (2007) report that particle size of plant material influences extraction efficiency. Increasing the particle size of sage leaves from 1 to 3 mm causes a decrease in the extraction yield and in the recovery of each bioactive component. However, if the particle size is too small it results in extraction difficulties, such as dust, heat generation during grinding and blocked filters. High temperatures and prolonged extraction times can also lead to increased solvent losses. Therefore, the recommended optimal extraction parameters are 2 nm particles, temperature 40 °C and duration 3 h. The optimal hydroalcoholic solvent composition was with between 55% and 75% ethanol.

Factors such as plant variety/cultivar, the part of the plant, the growing season and the particle size of the plant material have significant influence on the TPC, the polyphenolic profile, the concentration of individual compounds and the antioxidant activity of extracts. However, TPC does not correlate with antioxidant capacity. The antioxidant activity of plant extracts is determined by their qualitative composition and the amounts of individual polyphenols. Leaves are generally found to have the highest content of phenolics. The choice of extraction method, especially the type of solvent, extraction time and temperature, are very important for achieving the greatest extraction efficiency. Moreover, due to the different polarities of polyphenols, binary-solvent systems (a mixture of water and organic solvents) are more efficient extraction solutions than mono-solvent systems.

## Antimicrobial activity of polyphenolic extracts

Plant extracts contain large amounts of polyphenolic compounds, which are well known as antioxidants but may also be described as natural antimicrobial agents. They show inhibitory effects against both food spoilage microorganisms and food-borne pathogens. Thus, their potential as food preservatives is of great interest. The sensitivity of microorganisms to polyphenols depends on the species and strain, as well as on the molecular structure of the phenolic compounds. The composition and concentration of the extract also play important roles. From the point of view of the meat industry, the most pressing need is to investigate the effect of plant extracts on the growth of the predominant microflora in meat and meat products. Table 2 presents a review of the literature on the antimicrobial activity of plant extracts.

Studies have demonstrated that mixtures of polyphenols, such as plant extracts, have a stronger influence on the growth of microorganisms than individual compounds (Serra et al. 2008; Puupponen-Pimiä et al. 2001). According to Serra et al. (2008), grape extract containing quercetin at a concentration of 20 mg/L is more effective against *Bacillus cereus* than the same concentration of synthetic pure quercetin. The mixture totally inhibited the growth of these bacteria, whereas they continued to grow in the presence of quercetin. Puupponen-Pimiä et al. (2001) studied the antibacterial properties of pure flavonoids (including anthocyanins) and phenolic acids, as well as berry extracts. The strongest activity was shown by myricetin. However, the polyphenolic mixtures were more effective than pure compounds. Therefore, it appears that a positive synergetic effect may occur between the constituents of plant extracts, resulting in strong antimicrobial activity. Current studies are therefore focusing on the antimicrobial properties of polyphenolic mixtures, rather than on individual compounds. Extracts can be obtained from several parts of plants, such as the fruits, skin, leaves and flowers, each of which has a different composition and activity.

Berry fruits contain a variety of polyphenols, including flavonoids from the group of anthocyanins (Ma et al. 2018). Ellagitannins are complex phenolic polymers present in high quantities in raspberries, cloudberries, strawberries and cranberries (Kähkönen, Hopia, and Heinonen 2001). High levels of lignans have been detected in lingonberries, strawberries and cranberries (Smeds, Eklund, and Willför 2012). Nohynek et al. (2006) compared the sensitivity of severe human pathogens to extracts obtained from the following berry fruits: bilberry, lingonberry, cranberry, red raspberry, cloudberry, strawberry, black currant, sea buckthorn berry, chokeberry, highbush bilberry, rowanberry and crowberry. Cloudberry extract showed the strongest antimicrobial activity, followed by raspberry and strawberry extracts, whereas the lowest activities were observed for chokeberry, rowan berry, crowberry and buckthorn berry extracts. *Helicobacter pylori* and *B. cereus*. *Campylobacter jejuni* were the most sensitive, while *Candida albicans* were inhibited only by cloudberry, raspberry and strawberry extracts (characterized by high levels of ellagitannins).

Radovanović et al. (2013) studied the antimicrobial activity of three wild berry fruit species from Southeast Serbia: European cornel, blackthorn and wild blackberry. All the extracts showed strong antimicrobial activity with inhibition zones of 12.0–16.2 mm. *Klebsiella pneumoniae* was the most resistant microorganism. Its growth did not appear to have been inhibited by the extracts; however, this was not confirmed by the microdilution method, which suggests that more than one method should be used to appropriately evaluate the sensitivity of microorganisms. *Salmonella* Enteritidis was the most sensitive of the Gram-negative bacteria, while *Staphylococcus aureus* was the most sensitive Gram-positive bacteria. Blackthorn extract had a slightly stronger antibacterial effect compared to the other mixtures. Moreover, in almost all cases the MIC was equal to MBC, which means that the extracts had a mostly bactericidal effect.

Grapes are thought to be one of the best sources of beneficial antioxidants among fruits. Katalinić et al. (2010)

**Table 2.** Antimicrobial activity of plant extracts.

| Plant material | | | | | |
|---|---|---|---|---|---|
| Common name | Scientific name | Extraction solvent | Method of microbiological analysis | Target microorganisms | Reference |
| Grape skins and seeds | *Vitis vinifera* | Water | Microplate photometer method | Gram-negative bacteria: *Escherichia coli, Salmonella poona,* Gram-positive bacteria: *Bacillus cereus,* Yeasts: *Saccharomyces cerevisiae, Candida albicans* | Serra et al. (2008) |
| Blueberry<br>Raspberry<br>Lingonberry<br>Blackcurrant<br>Cloudberry<br>Cranberry<br>Sea buckthorn berry<br>Strawberry | *Vaccinium myrtillus*<br>*Rubus idaeus,* var. Ottawa<br>*Vaccinium vitis-idaea*<br>*Ribes nigrum* var. Öjeby<br>*Rubus chamaemorus*<br>*Vaccinium oxycoccus*<br>*Hippophae rhamnoides*<br>*Fragaria ananassa* Senga Sengana | Acetone/ water (70/30 v/v) | Disc diffusion method, plate count method (bacterial growth curve measurement) | Gram-negative bacteria: *Escherichia coli, Salmonella enterica* Typhimurium<br>Gram-positive bacteria: *Bifidobacterium lactis, Enterococcus faecalis, Lactobacillus crispatus, Lactobacillus johnsonii, Lactobacillus paracasei, Lactobacillus plantarum, Lactobacillus reuteri, Lactobacillus rhamnosu,* | Puupponen-Pimiä et al. (2001) |
| Bilberry<br>Lingonberry<br>Cranberry<br>Red raspberry<br>Cloudberry<br>Strawberry<br>Black currant<br>Sea buckthorn berry<br>Chokeberry<br>Highbush bilberry<br>Rowanberry<br>Crowberry | *Vaccinium myrtillus*<br>*Vaccinium vitis-idaea*<br>*Vaccinium oxycoccus*<br>*Rubus idaeus* var. Ottawa<br>*Rubus chamaemorus*<br>*Fragaria ananassa* Senga Sengana<br>*Ribes nigrum* var. Öjeby<br>*Hippophae rhamnoides*<br>*Aronia mitschurinii*<br>*Vaccinium myrtillus*<br>*Sorbus aucuparia*<br>*Empetrum nigrum* | Acetone/water (70/30 v/v) | Plate count method | Gram-negative bacteria: *Escherichia coli, Salmonella enterica* Infantis*, S. enterica* Typhimurium, *Helicobacter pylori, Campylobacter jejuni,*<br>Gram-positive bacteria: *Bacillus cereus, Clostridium perfringens, Lactobacillus rhamnosus, Staphylococcus aureus, Staphylococcus epidermidis*<br>Yeasts: *Candida albicans* | Nohynek et al. (2006) |
| Wild blackberry<br>European cornel<br>Blackthorn | *Rubus fruticosus*<br>*Cornus mas*<br>*Prunus spinosa* | Formic acid/methanol/ water (0.1/70/29.9 v/ v/v) | Disc diffusion method broth microdilution method | Gram-negative bacteria: *Escherichia coli, Pseudomonas aeruginosa,* *Salmonella enteritidis*, *Shigella sonnei*, *Klebsiella pneumoniae*, *Proteus vulgaris*<br>Gram-positive bacteria: *Clostridium perfringens*, *Bacillus subtilis*, *Listeria innocua*, *Staphylococcus aureus*, *Sarcina lutea, Micrococcus flavus,* | Radovanović et al. (2013) |
| Grape skin | *Vitis vinifera* (white varieties: Debit, Kuč, Kujundžuša, Maraština, Medna, Rkaciteli*, Zlatarica; red varieties: Babić, Lasin, Merlot*, Plavina, Rudežuša, Trnjak, Vranac | Ethanol/water (80/20, v/ v) | Broth microdilution method | Gram-negative bacteria*: Escherichia coli* O157:H7*, and Salmonella Infantis, Campylobacter coli*<br>Gram-positive bacteria: *Bacillus cereus, Staphylococcus aureu* | Katalinić et al. (2010) |
| Grape pomace | *Vitis vinifera* (Merlot and Syrah varieties) | Ethanol/ethyl acetate/hexane | Disc diffusion method broth microdilution method | Gram-negative bacteria: *Escherichia coli, Pseudomonas aeruginosa*<br>Gram-positive bacteria: *Staphylococcus aureus, Bacillus cereus*<br>Yeasts: *Candida albicans, Candida parapsilosis, Candida krusei* | Oliveira et al. (2013) |
| Grape seeds | *Vitis vinifera* | Ethanol/water (50/50 v/v) | Agar well diffusion method | Gram-negative bacteria*: Escherichia coli, Pseudomonas aeruginosa*<br>Gram-positive bacteria*: Staphylococcus aureus, Micrococcus luteus,*<br>Molds: *Aspergillus niger, Fusarium oxysporum* | Ghouila et al. (2017) |
| Plums<br>Red grapes<br>elderberry fruits | *Prunus domestica*<br>*Vitis vinifera*<br>*Sambucus nigra* | Ethanol/water (70/30 v/v) | Agar well diffusion method | Gram-negative bacteria*: Escherichia coli*<br>Gram-positive bacteria: *Bacillus* | Coman et al. (2017) |

(*continued*)

**Table 2.** Continued.

| Plant material | | Extraction solvent | Method of microbiological analysis | Target microorganisms | Reference |
|---|---|---|---|---|---|
| Common name | Scientific name | | | | |
| | | | | *cereus, Lactobacillus paracasei,, Lactobacillus plantarum, Lactobacillus rhamnosus, Listeria monocytogenes, Staphylococcus aureus* Yeasts: *Candida albicans* | |
| Pomegranate peels | *Punica granatum (*Mollar de Elche, Valenciana de Albatera, Piñón Tierno de Ojós, Hicaznar, Borde de Albatera, Borde de Beniel cultivars | Methanol/water (70/30 v/v) | Radial growth inhibition Broth microdilution method | Gram-negative bacteria: *Escherichia coli, Shigella sonnei, Salmonella enterica* subsp. *Enterica* Gram-positive bacteria: *Bacillus subtilis* subsp. *Spizizenii, Enterococcus faecalis, Staphylococcus aureus* subsp. *aureus* Moulds: *Aspergillus flavus, Aspergillus parasiticus, Gibberella fujikuroi* var. Fujikuroi, *Alternaria alternate, Botryotinia fuckeliana* | Rosas-Burgos et al. (2017) |
| Pomegranate peels | *Punica granatum* L. (Hicaznar) | Methanol/water (80/20 v/v) + 0.01% HCl | A broth dilution method spread plate method (survival curves) | Gram-negative bacteria: *Cronobacter sakazakii* strains | Polat Yemis, Bach, and Delaquis (2019) |
| Green tea | *Camellia sinensis* | – | Plate count method | Gram-negative bacteria: *Escherichia coli, Enterobacter cloacae, Neisseria meningitidis* Gram-positive bacteria: *Lactobacillus acidophilus, Lactobacillus plantarum, Streptococcus mutans, Streptococcus sanguis, Streptococcus sobrinus, Streptococcus mitis, Streptococcus salivarius, Staphylococcus aureus, Enterococcus faecalis,* Yeasts: *Candida albicans* | Cho, Oh, and Oh (2010) |
| Green tea | *Camellia sinensis* | – | Agar dilution method | Gram-positive bacteria: *Staphylococcus aureus(MSSA and MRSA strains)* | Cho, Schiller, and Oh (2008) |
| Green tea | *Camellia sinensis* | Water | Turbidity measurement | Gram-negative bacteria: *Pseudomonas aeruginosa* Gram-positive bacteria: *Staphylococcus aureus,* | Bazzaz et al. (2016) |
| Rooibos<br>Green tea<br>Black tea<br>Rosemary<br>Lemongrass<br>Mulberry leaf<br>Bamboo leaf<br>Lotus leaf<br>Peppermint<br>Persimmon leaf<br>Mate tea | *Aspalathus linearis*<br>*Camellia sinensis*<br>*Camelia sinensis,*<br>*Rosmarinus officinalis*<br>*Cymbopogon citrates*<br>*Morus alba*<br>*Sasa borealis*<br>*Nelumbo nucifera*<br>*Mentha piperita,*<br>*Diospyros kaki*<br>*Ilex paraguariensis* | Water<br>ethanol/water (90/10 v/v) | Broth microdilution method | Gram-negative bacteria: *Shigella flexneri, Salmonella enterica* Gram-positive bacteria: *Streptococcus mutans, Streptococcus sobrinus, Listeria monocytogenes* | Oh et al. (20130 |
| Green tea<br>Black tea | *Camellia sinensis*<br>*Camellia sinensis* | Water | Broth microdilution method | Gram-negative bacteria: *Pseudomonas aeruginosa, Escherichia coli* Gram-positive bacteria: *Enterococcus faecalis, Staphylococcus aureus* | Bancirova (2010) |
| Thyme<br>Rosemary<br>Oregano<br>Peppermint<br>Sage | *Thymus vulgaris*<br>*Rosmarinus officinalis*<br>*Origanum vulgare*<br>*Mentha piperita*<br>*Salvia officinalis* | Ethanol/water (70/30 v/v) methanol/water (70/30 v/v) | Disc diffusion method | Gram-negative bacteria: *Escherichia coli, Klebsiella pneumoniae, Proteus vulgaris, Proteus mirabilis, Stenotrophomonas maltophilia, Pseudomonas aeruginosa, , Bordetella bronchiseptica* Gram-positive bacteria: *Staphylococcus aureus,* | Kozlowska et al. (2015) |

(*continued*)

**Table 2.** Continued.

| Plant material | | Extraction solvent | Method of microbiological analysis | Target microorganisms | Reference |
|---|---|---|---|---|---|
| Common name | Scientific name | | | | |
| | | | | *Staphylococcus epidermidis, Enterococcus faecalis, Enterococcus hirae, Bacillus subtilis, Geobacillus stearothermophilis, Listeria monocytogenes,* | |
| Turmeric | *Curcuma longa* | Ethanol | Agar well diffusion method | Gram-negative bacteria: *Serratia* sp. | Dhiman et al. (2016) |
| Ginger | *Zingiber officinale* | methanol | | Gram-positive bacteria: *Bacillus cereus* | |
| Wild mint | *Mentha arvensis* | acetone | | Yeasts: *Rhodotorula mucilaginosa* | |
| Ashwagandha | *Withania somnifera* | water | | Molds: *Aspergillus flavus, Penicillium citrinum* | |
| Indian snakeroot | *Rauvolfia serpentina* | | Radial growth inhibition | | |
| Amla | *Emblica officinalis* | | | | |
| Arjuna | *Terminalia arjuna* | | | | |
| Centella | *Centella asiatica* | | | | |
| Caraway | *Carum carvi* | Methanol/water (80/20 v/v) | Agar well diffusion method | Gram-negative bacteria: *Escherichia coli, Salmonella anatum* | Shan et al. (2007) |
| Cinnamon | *Cinnamomum cassia* | | | Gram-positive bacteria: *Bacillus cereus, Listeria monocytogenes, Staphylococcus aureus,* | |
| Cinnamon | *Cinnamomum burmannii* | | | | |
| Coriander | *Coriandrum sativum* | | | | |
| Cumin | *Cuminum cyminum* | | | | |
| Clove | *Eugenia caryophylata* | | | | |
| Star anise | *Illicium verum* | | | | |
| Bay | *Laurus nobilis* | | | | |
| Mint | *Mentha canadensis* | | | | |
| Nutmeg | *Myristica fragrans* | | | | |
| Sweet basil | *Ocimum basilicum* | | | | |
| Oregano | *Origanum vulgare* | | | | |
| Parsley | *Petroselinum crispum* | | | | |
| Green peppercorn | *Piper nigrum* | | | | |
| Black pepper | *Piper nigrum* | | | | |
| White pepper | *Piper nigrum* | | | | |
| Rosemary | *Rosmarinus officinalis* | | | | |
| Sage | *Salvia officinalis* | | | | |
| Thyme | *Thymus vulgaris* | | | | |
| Chinese prickly ash | *Zanthoxylum bungeanum* | | | | |
| Betelnut | *Areca catechu* | | | | |
| Yinchenhao | *Artemisia capillaris* | | | | |
| Qinghao | *Artemisia caruifolia* | | | | |
| Huangqi | *Astragalus mongholicus* | | | | |
| Chaihu | *Bupleurum scorzonerifolium* | | | | |
| Lingxiaohua | *Campsis radicans* | | | | |
| Cassia | *Cassia auriculata* | | | | |
| Juhua | *Chrysanthemum morifolium* | | | | |
| Shanyu | *Cornus officinalis* | | | | |
| Jinqiaomai | *Fagopyrum cymosum* | | | | |
| Yuxingcao | *Houttuynia cordata* | | | | |
| Xuanfuhua | *Inula britannica* | | | | |
| Jinyinhua | *Lonicera japonica* | | | | |
| Guanzhong | *Matteuccia struthiopteris* | | | | |
| Cow-itch plant | *Mucuna pruriens* | | | | |
| Box myrtle | *Myrica nagi* | | | | |
| Huangbo | *Phellodendron murensea* | | | | |
| Huzhang | *Polygonum uspidatumc* | | | | |
| Heshouwu | *Polygonum multiflorum* | | | | |
| Xiaku | *Prunella vulgaris* | | | | |
| Shiliupi | *Punica granatum* | | | | |
| – | *Rhus succedanea* | | | | |
| Diyu | *Sanguisorba officinalis* | | | | |
| Huangqin | *Scutellaria baicalensis* | | | | |
| Belliric myrobalan | *Terminalia bellirica* | | | | |
| Diding | *Viola yedoensis* | | | | |
| Great burnet | *Sanguisorba ofcinalis* | Ethanol/water (70/30 v/v) | Oxford cup method microdilution method | Gram-negative bacteria: *Escherichia coli, Salmonella* Typhimurium | Zhu et al. (2019) |
| | | | | Gram-positive bacteria: *Staphylococcus aureus, Listeria monocytogenes, Bacillus subtilis* | |
| Clove | *Syzygium aromaticum* | Water | Agar well diffusion method | Gram-negative bacteria: *Pseudomonas Fluorescens, Shewanella putrifaciens, Escherichia coli, Salmonella typhimurium* | Radha Krishnan et al. (2014) |
| Cinnamon | *Cinnmomum cassia* | | Broth microdilution method | | |
| Oregano | *Origanum vulgare* | | | | |
| Mustard | *Brassica nigra* | | | | |

(*continued*)

**Table 2.** Continued.

| Plant material | | Extraction solvent | Method of microbiological analysis | Target microorganisms | Reference |
|---|---|---|---|---|---|
| Common name | Scientific name | | | | |
| Walnut leaves | *Juglans regia* | Water | Agar well diffusion method | Gram-positive bacteria: *Listeria monocytogenes, Lactococuus lactis, Leuconostoc mesenteroides,* Gram-negative bacteria*: Escherichia coli, Pseudomonas aeruginosa, Klebsiella pneumoniae* Gram-positive bacteria: *Bacillus. cereus, Bacillus subtilis, Staphylococcus aureus* Yeasts: *Candida albicans, Candida neoformans* | Pereira, Oliveira, et al. (2007) |
| Grape leaves | *Vitis vinifera* (white varieties: *Maraština, Pošip*; red varieties: *Lasin, Merlot, Syrah, Vranac* | Ethanol/water (80/20 v/v) | Broth microdilution method | Gram-negative bacteria: *Escherichia coli, Salmonella Infantis, Campylobacter jejuni* Gram-positive bacteria: *Stapylococcus aureus, Bacillus cereus,* | Katalinic et al. (2013) |
| Olive leaves | *Olea europaea* | Ethanol/water (80/20 v/v) | Broth microdilution method | Gram-negative bacteria: *Escherichia coli* O157:H7, *Salmonella* Enteritidis Gram-positive bacteria: *Listeria monocytogenes,* | Liu, McKeever, and Malik (2017) |

investigated the antibacterial activity of grape skin extracts obtained from 14 *Vitis vinifera* varieties (seven white and seven red varieties) grown in Dalmatia (Croatia). Their antimicrobial effects were tested against Gram-positive (*S. aureus*, *B. cereus*) and Gram-negative bacteria (*Escherichia coli* O157:H7, *Salmonella* Infantis, *Campylobacter coli*). All the extracts were active against all the screened microorganisms, with MICs ranging from 0.014 to 0.59 $mg_{GAE}$/mL depending on the bacteria species and extract. No significant differences in the susceptibility of Gram-positive and Gram-negative bacteria were noted. The most sensitive was *C. coli*. followed by *S.* Infantis. Interestingly, white varieties showed lower MIC values than red varieties.

Oliveira et al. (2013) report that Gram-positive bacteria (*S. aureus* and *B. cereus*) are more susceptible to grape extracts than Gram-negative bacteria (*E. coli* and *Pseudomonas aeruginosa*). *P. aeruginosa* and *C. albicans* were found to be the most resistant microorganisms. Ghouila et al. (2017) investigated the antibacterial activity (against two strains of *S. aureus, Micrococcus luteus, E. coli* and *P. aeruginosa*) and antifungal activity (against *Aspergillus niger* and *Fusarium oxysporum*) of grape seed extract obtained using the well-diffusion method. All the microorganisms were susceptible to the extract (100 µg/mL and 1000 µg/mL), except for one *S. aureus* strain which was also resistant to methicillin. The strong antimicrobial activity of grape seeds could be due to the wide variety of procyanidins they contain.

Coman et al. (2017) investigated the antimicrobial properties of red fruit extracts obtained from plums, Italian red grapes and elderberry fruits. The extracts showed antibacterial activity against the pathogens *B. cereus, S. aureus* and *E. coli*. The yeast *C. albicans* was more resistant. Interestingly, the extracts stimulated the growth of probiotic bacteria.

Rosas-Burgos et al. (2017) studied the antibacterial and antifungal activity of different cultivars (sweet, sour-sweet and sour) of pomegranate peel crude extract. They found that the sour-sweet PTO8 pomegranate cultivar, which showed the highest ellagic acid concentration, was the most active. This extract (5 mg/mL) inhibited the growth of fungi with inhibition values of 39.2%, 70.0%, 50.0% and 50.8% for *Aspergillus flavus*, *Fusarium verticillioides*, *Alternaria alternata* and *Botrytis cinerea*, respectively. The PTO8 cultivar showed the lowest MIC50 and MIC90 values against *E. coli, Shigella sonnei* and *B. subtilis*, followed by the HIC cultivar. Against *Salmonella enterica*, *Enterococcus faecalis* and *S. aureus*, the lowest MIC50 and MIC90 values were detected for sour cultivar HIC, followed by PTO8. Generally, Gram-positive bacteria were more susceptible to the pomegranate extracts than Gram-negative bacteria.

Polat Yemis, Bach, and Delaquis (2019) investigated antibacterial activity of phenolic extract from pomegranate peel against three *Cronobacter sakazakii* isolates. The extract showed concentration-dependent bacteriostatic and bactericidal effects that increased with decreasing incubation temperature and pH of extract. MIC values ranged from 0.42 mg/mL to 20.00 mg/mL and MBC values ranged from 8.22 mg/mL to 50.00 mg/mL. However, survival curves showed that lethality increased at 37 °C. The most rapid population decline was observed at pH 4.0 and a temperature of 37 °C. The level of microorganisms decreased by 4 log CFU/mL after 24 h and *C. sakazakii* was not recovered by enrichment after 48 h. In contrast, the population was reduced by 0.5 log CFU/mL after 24 h at pH 4.0 and 10 °C, and only after 8 days of incubation was *C. sakazakii* not recovered by enrichment.

In recent years, the health benefits of green tea have become more widely known. Green tea can play an

important role in preventing obesity, as well as having other advantages such as anticaries-properties and preventing periodontal disease. These properties are associated with the antimicrobial activity of green tea extract. Its antimicrobial effect is related to the high content of catechin derivatives such as EGCG and ECG (Taylor, Hamilton-Miller, and Stapleton 2005). Cho, Oh, and Oh (2010) investigated the antimicrobial activity and inhibition of biofilm formation by tea polyphenols extracted from Korean green tea (*Camellia sinensis* L) against 12 oral pathogens. Their in vitro studies revealed that the most sensitive pathogen was *Streptococcus sanguinis*, which was killed immediately when treated with green tea extract at a concentration of 2,000 μg/mL. Other strains were also very sensitive and the elimination effect was achieved after 5 min of incubation. The green tea extract in addition significantly inhibited biofilm formation on human teeth.

Some studies have shown that green tea polyphenols can have a synergistic effect in combination with antibiotics. Cho, Schiller, and Oh (2008) evaluated the effect of green tea extract on clinical isolates of methicillin-resistant *S. aureus* (MRSA). The MICs of the tea extract were in the range of 50–180 μg/mL for both MSSA and MRSA strains. When MRSA strains were incubated with oxacillin + green tea polyphenols at sub-MIC (≥0.5x MIC), the MICs were reduced between 8- and 128-fold compared to oxacillin alone. Bazzaz et al. (2016) observed a synergistic effect between catechin derivatives and green tea extracts with gentamycin. The MICs of gentamicin against *S. aureus* and *P. aeruginosa* strains were in the range of 0.312–320 μg/mL, whereas the MIC values of catechin derivatives (EGC, EGCG) were 62.5–250 μg/mL and for green tea extract 250–1000 μg/mL. However, when gentamycin was combined with green tea extract or catechins, the MIC values were reduced by up to twofold.

Green tea is generally considered to have superior antioxidant properties and antimicrobial properties to black tea. This is due to differences in the manufacturing process. Green tea is a non-fermented tea, which is produced by drying and steaming the fresh leaves. Black tea is a fermented tea, which is fermented before drying and steaming. Oh et al. (2013) studied the antimicrobial properties of water and ethanol extracts of leafy herbal teas (rooibos, green tea, black tea, rosemary, lemongrass, mulberry leaf, bamboo leaf, lotus leaf, peppermint, persimmon leaf and mate) against oral pathogens (*Streptococcus mutans* and *Streptococcus sobrinus*) as well as food-borne pathogens (*Listeria monocytogenes, Shigella flexneri* and *S. enterica*). Green tea ethanol extract was the most active, inhibiting the growth of all the tested pathogens (for all bacteria MIC = 10 mg/mL). Interestingly, although the green tea and black tea extracts showed similar antioxidant activity, their antimicrobial activities differed. Black tea did not inhibit any of the studied microorganisms, possibly due to changes to is composition incurred during the manufacturing process. According to Kim et al. (2011), catechins, the main components of tea responsible for its antimicrobial properties, are lost during the fermentation process. Galloyl groups are released from gallated catechins, which are further transformed to theaflavins. However, when Bancirova (2010) compared the antibacterial activities of green and black teas against selected Gram-positive (*E. faecalis, S. aureus*) and Gram-negative strains (*P. aeruginosa, E. coli*), no differences in either antimicrobial effect or antioxidant activity were noticed. These inconsistent results may be due to differences in the geographical origins of the teas, the leaf ages or leaf quality.

The ability of herbs and spices to improve food properties such as taste or flavor, as well as their ability to preserve food medicinal properties, have long been recognized. However, the nutritional value of herbs and spices has been less widely studied. Herbs and spices reveal strong antimicrobial and antioxidant properties, which are associated with their high contents of essential oils and polyphenols (Embuscado 2015).

Kozlowska et al. (2015) investigated the antibacterial properties of methanolic and ethanolic extracts obtained from herbs commonly used in Poland: thyme, rosemary, oregano, peppermint and sage. Rosemary extracts were found to be the most active, exhibiting inhibitory effects against all the tested Gram-positive bacteria (IZ = 12–19 mm and MIC = 0.125–0.5 mg/mL) and four Gram-negative bacteria (IZ = 11–17 mm and MIC = 0.25–0.5 mg/mL). *S. aureus* strains were the most susceptible bacteria to rosemary and sage extracts as well as to aqueous methanolic thyme extract. *K. pneumoniae* and *Proteus vulgaris* were the most sensitive to aqueous methanolic thyme extract, whereas *L. monocytogenes* showed the greatest susceptibility to aqueous ethanolic rosemary extract. Generally, Gram-negative bacteria were more resistant to the herb extracts than Gram-positive bacteria. These results suggest that the type of extraction solvent used can determine not only the polyphenolic content and the antioxidant capacity of the extract, but also its antimicrobial properties.

According to studies by Dhiman et al. (2016), herbs are also effective against molds and yeasts. The broadest spectrum of antimicrobial activity was shown by *Centella asiatica, Emblica officinalis* and *Terminalia arjuna*, which inhibited the growth of bacteria and fungi. The most sensitive bacteria were *B. cereus* and the most resistant yeasts were *Rhodotorula mucilaginosa.* Extracts of *C. asiatica* displayed the greatest inhibition zone against bacteria and yeasts and the greatest mycelial inhibition against molds.

Shan et al. (2007) studied the antibacterial properties of 46 extracts of dietary spices and medicinal herbs against foodborne pathogens: *B. cereus, L. monocytogenes, S. aureus, E. coli* and *Salmonella anatum*. High activity was exhibited against all the tested bacteria by 12 extracts (*Punica granatum, Myrica nagi, Sanguisorba officinalis, Areca catechu, Eugenia caryophylata, Polygonum cuspidatum, Rhus succedanea, Matteuccia struthiopteris, Origanum vulgare, Cinnamomum burmannii B., Terminalia belliric* and *Cassia auriculata*). The medicinal herbs were revealed to have significantly stronger properties than the dietary spices. The Gram-positive bacteria were generally more sensitive than the Gram-negative strains. *S. aureus* was the most susceptible bacteria, while the most resistant was *E. coli*. A high

correlation was noted between TPC and antibacterial activity ($R^2$ = 0.72–0.93).

Zhu et al. (2019) demonstrated antibacterial activity of polyphenolic constituents from *Sanguisorba offcinalis* (crude and purified polyphenolic extracts). It was shown that inhibition zones of three Gram-positive bacteria, *S. aureus, B. subtilis, L. monocytogenes*, in the purified extract group (29.41, 27.15, 24.66 mm) were twice as large as in the crude extract group (15.18, 13.85 and 14.78 mm,). Among Gram-negative bacteria group, inhibition zones of *E. coli* and *S.* Typhimurium were only 7.23 and 10.62 mm in crude extract group, but increased to 10.90 and 14.73 mm in purified extract group. MIC and MBC values in purified extract group were lower than in crude extract group. These results suggest that purified extract is more active than crude extract. Moreover, Gram-positive bacteria are more susceptible to *S. offcinalis* extract than Gram-negative bacteria.

Radha Krishnan et al. (2014) studied the antibacterial activity of dried spice extracts (clove, cinnamon, oregano, mustard). Using the agar well diffusion assay, the antibacterial activity was found to be as follows: clove > cinnamon > oregano > mustard. *Lactococcus lactis* was the most susceptible bacteria. The MIC values were also determined. The most susceptible bacteria were *P. fluorescens, E.coli* and *Shawanella putrifaciens* (MIC = 10–20 mg/mL), while *Salmonella* Typhimurium was the most resistant (20–30 mg/mL).

As mentioned previously, leaves contain larger amounts of polyphenolic compounds than the other parts of plants. Nevertheless, there has been little research into the antimicrobial activity of leaf extracts. Most studies focus on the antimicrobial properties of the leaves of herbs, whereas few have looked at leaves from fruit trees and shrubs. Pereira, Oliveira, et al. (2007) demonstrated that walnut leaf extract was effective only against Gram-positive bacteria, in the following order: *B. cereus* > *S. aureus* > *Bacillus subtilis*. *B. cereus* was inhibited at a concentration of 0.1 mg/mL, while fungi and Gram-negative bacteria were resistant even at the highest studied concentration (100 mg/mL). Katalinic et al. (2013) investigated the antimicrobial activity of leaf extracts from six *Vitis vinifera* varieties collected in May, August and September. The sensitivity of the bacteria was as follows: *B. cereus* (MIC = 0.77 mg/mL)>*Campylobacter jejuni* (MIC = 1.03 mg/mL)>*S. aureus* (MIC = 1.11 mg/mL)>*E. coli* (MIC = 1.39 mg/mL)>*S.* Infantis (MIC = 1.50 mg/mL). Lower MIC values were measured for leaves collected in August and September, which correlates with the phenolic content.

Pereira, Ferreira, et al. (2007) studied the antimicrobial properties of olive leaf extract against microorganisms associated with food quality degradation and intestinal infections. The extract inhibited the growth of all the tested microorganisms, decreasing their growth rates in a concentration-dependent manner. The sensitivity of the bacteria and fungi was as follows: *B. cereus* ~ *C. albicans* > *E. coli* > *S. aureus* > *Cryptococcus neoformans* ~ *K. pneumoniae* ~ *P. aeruginosa* > *B. subtilis*. For *B. cereus* and *C. albicans*, the $IC_{25}$ were less than 1 mg/mL. Moreover, the extract at a concentration of 5 mg/mL decreased the $OD_{540}$ after 24 h and 48 h of incubation. Liu, McKeever, and Malik (2017) found that olive leaf extract (62.6 mg/mL), completely inhibited the growth of *L. monocytogenes* and *S.* Enteritidis and almost completely inhibited the growth of *E. coli* O157:H7 (by 95%). Oleuropein and vabascoside, which are the major compounds in olive leaf extract, showed potent antibacterial activity. This suggests that they may be the primary components responsible for the inactivation of foodborne pathogens.

Natural extracts can also be obtained from production wastes. Serra et al. (2008) studied the influence of extracts derived from wastes from olive oil and wine production on the growth kinetics of *E. coli, Salmonella poona, B. cereus, Saccharomyces cerevisiae* and *C. albicans*. The grape extract was more effective than the olive extract and showed stronger activity against a Gram-positive strain of *B. cereus*. At a concentration of 40 mg/L, the extract totally inhibited the growth of *B. cereus* over a 72 h period. The olive extract was also more active against *B. cereus*. At a concentration of 75 mg/L the effect was very strong but after 72 h of incubation the bacteria recovered.

Plant extracts rich in phenolic compounds are found to show stronger antimicrobial activity than single compounds. They can exhibit antimicrobial activity against both food spoilage microorganisms and foodborne pathogens, including bacteria, yeasts and molds. However, fungi are generally more resistant to polyphenolic extracts than bacteria. The literature further suggests that Gram-positive bacteria are more susceptible to polyphenols than Gram-negative bacteria. As we have seen in this review, plants such as fruit trees and shrubs, tea trees, herbs, spices and medicinal plants can be rich sources of polyphenols, indicating possible antimicrobial properties. Moreover, extracts can be obtained from different parts of plants such as fruits, leaves, flowers, stems, peels, seeds and skin. The biological properties of the extracts are determined by their composition.

## Mechanism of antibacterial activity

The exact mechanism of antibacterial action by polyphenols is still unclear and requires further investigation. Phenolic compounds can have a diverse range of chemical structures, which means that there are many possible mechanisms of antimicrobial activity. Moreover, most studies have focused on investigating not single compounds but extracts, which are mixtures of polyphenols belonging to different groups. This suggests that phenolic compounds have multidimensional activities. In addition, interactions between polyphenols in mixtures may also influence their mechanisms of action.

Some studies have demonstrated that phenolic compounds interact with bacterial cell walls, leading to disruption of the cell wall and the release of cellular contents. Cell wall damage decreases cell resistance to unfavorable conditions such as high or low osmotic pressure and different external factors. The available data show that Gram-negative bacteria are more resistant to phenolic compounds. This is probably related to the presence of a lipophilic outer

membrane containing high levels of phospholipids. This makes the cell wall impermeable to several macromolecules. The high resistance of Gram-negative bacteria to phenolic compounds may also be associated with enzymes in the periplasma space, which can damage molecules introduced from outside (Konaté et al. 2012). Nonetheless, other studies have suggested that polyphenols can disintegrate the outer membrane of Gram-negative bacteria, leading to increases in membrane permeability (Plumed-Ferrer et al. 2013; Yi et al. 2010; Nohynek et al. 2006). According to Nohynek et al. (2006), berry phenolics can reduce outer membrane permeability in a similar manner to EDTA by releasing LPS and chelating divalent cations or by intercalating into the outer membrane and replacing stabilizing cations.

Polyphenols also cause disruption in bacteria cell membranes (the inner membrane), resulting in the loss of chemiosmotic control and leading to cell death. This is probably caused by the ability of polyphenols to bind proteins associated with the cell membrane. It has been reported that tea polyphenols increase the permeability of the inner membrane in *P. aeruginosa* and *Serratia marcescens* cells (Yi et al. 2014, Yi et al. 2010). This is probably due to the high content of catechin derivatives. Cao et al. (2019) report that EGCG causes damage to the *E. coli* cell membrane. Bhattacharya et al. (2018) have demonstrated that Kombucha polyphenolic fraction containing mainly catechin and isorhamnetin as well as catechin and isorhamnetin alone show the ability to permeabilize the inner membrane of *Vibrio cholera*.

Microscopic techniques such as AFM, SEM and TEM enable the observation of morphological changes in bacterial cells. The AFM technique can be very useful for describing the topography of cell surfaces. Generally, polyphenols cause disruption of the cell wall and the release of the cellular contents. Changes in cell shape, irregular forms and wrinkles on the surfaces of bacteria can be observed (Cho et al. 2007; Lou et al. 2011). Cui et al. (2012) used AFM to study morphological alterations in Gram-positive and Gram-negative bacteria induced by EGCG. The EGCG induced aggregates in the cell envelope of *S. aureus* and caused cell lysis. In *E. coli* cells, nanoscale perforations or microscale grooves in the cell wall were observed. Moreover, EGCG induced oxidative stress in Gram-negative cells. These results suggest that the mechanisms of antibacterial action against Gram-positive and Gram-negative bacteria differ. Deterioration of the cell walls of *S. aureus* is probably caused by EGCG binding to the peptidoglycan layer, while in *E. coli* cell wall damage is due to oxidative stress and the production of $H_2O_2$.

Studies have confirmed that phenolic compounds can induce endogenous oxidative stress in bacteria cells, by inducing ROS formation. *Scutellaria barbata*, *Mentha arvensis* and EGCG extracts have been reported increasing intracellular ROS generation, which can lead to cell death (Tang, Kang, and Lu 2016; Zhang et al. 2015; Xiong et al. 2017). The ability of polyphenols to induce ROS production could be due to their prooxidant properties. When oxidized, phenolic compounds can transform into prooxidant forms and cause $H_2O_2$ generation via Fenton reactions. In the presence of transition metals (Cu(I) or Fe(II)) they can cause the generation of • OH from $H_2O_2$ (Brudzynski, Abubaker, and Miotto 2012; Brudzynski and Lannigan 2012). Cho et al. (2007) reported changes in the cellular fatty acid composition of *E. coli* caused by green tea polyphenols. It was suggested that these membrane fatty acid shifts can cause membrane deterioration.

As mentioned previously, cell wall perturbations can lead to the leakage of intracellular components. Studies have demonstrated that plant extracts can cause significant increases in intracellular protein leakage in bacterial cultures, depending on the concentration and the length of incubation (Tang, Kang, and Lu 2016; Zhang et al. 2015). Polyphenols have also been shown to cause the release of cytoplasmic constituents, such as nucleotides and small cellular molecules e.g. potassium and phosphate ions (Stojković et al. 2013; Yi et al. 2010; Lou et al. 2011).

Recent studies have shown that there is a relationship between the activity of flavonoids and their structure, such as the number and position of hydroxyl groups or methoxyl groups. Wu, He, et al. (2013b) demonstrated that hydroxyl groups at C-5 in the A ring and C-4′ in the B ring as well as methoxyl groups at C-3 and C-8 in the A ring of flavonoids increase their inhibitory effects. However, hydroxyl groups at C-6 in the A ring, at C-3′ and C-5′ in the B ring and at C-3 in the C ring or methoxyl groups at C-3′ in the B ring contribute to reduce the activity of flavonoids. Wu, He, et al. (2013a) have shown that 5 flavonoids rigidified the liposomal model membrane (kaempferol > chrysin > quercetin > baicalein > luteolin), whereas polymethoxyflavones and isoflavonoids increased membrane fluidity (puerarin > ononin > daidzein > genistin > 5,6,7,4′-tetramethoxyflavone > tangeritin). This effect contributes to strengthen antibacterial activity. A quantitative structure-activity relationship study showed that the activity of flavonoids is associated with molecular hydrophobicity and OH groups situated at position 3 in the C-ring.

Other studies have demonstrated that the antibacterial activity of catechins is strongly related to their hydrophobicity. Kamihira et al. (2008) investigated the interactions between tea catechins and lipid bilayers. They found that ECG and EGCG revealed about 1000 times stronger affinity to lipid bilayers than EC or EGC. The results of their study show that the presence of galloyl groups in the structure of catechins significantly increases their hydrophobicity and affinity to lipid bilayers.

Hashimoto et al. (1999) observed perturbations in the membrane structures of catechins in the presence of EGCG and ECG. They suggest that the high affinity of catechins with galloyl groups to lipid bilayers determines the membrane structure and influences their antibacterial activity. Kajiya et al. (2004) report that the antibacterial activity of catechins and their affinity to lipid bilayers increase with the number of carbon atoms in their alkyl chain. The most potent antibacterial activity may be observed when the alkyl chain is composed of 4–7 carbon atoms. The strongest affinity to the membrane occurs in the case of derivatives containing three or more carbon atoms in the alkyl chain.

Moreover, liposomes treated with catechins with longer carbon chains (C5-C10) leak a fluorescenct substance (calcein), which indicates that these derivatives are able to destroy membranes by increasing lipophilicity.

Polyphenols can also influence the biosynthesis of proteins in bacterial cells and thus change their metabolic processes. Metabolic disorders can result in bacteria cell death. Yi et al. (2010) studied differences in the membrane proteins of *P. aeruginosa* cells treated with tea polyphenols. In total, 27 differentially expressed proteins were detected in cells treated with tea extract. Most were enzymes involved in metabolic processes, such as the tricarboxylic acid cycle (dihydrollpoamide dehydrogenase, succinyl Co-A synthetase beta subunit), fatty acid biosynthesis (dihydrollpoamide dehydrogenase dehydrogenase, biotin carboxyl carrier protein), protein biosynthesis (elongation factor Ts (EF-Ts), 50 s ribosomal protein), glycine metabolism (glycine cleavage system protein T2), DNA metabolism (single-stranded DNA-binding protein) or synthesis of intracellular polyamines (polyamine transport protein). Cho et al. (2007) also report changes in protein synthesis by *E. coli* cells exposed to green tea polyphenols. The expression of nine proteins was upregulated (including chaperon protein HSP and proteins involved in cellular defense (GyrA, RpoS, SodC, EmrK)), whereas eight proteins were downregulated (including proteins involved in carbon and energy metabolism (Eno, SdhA, UgpQ) and those involved in amino-acid biosynthesis (GltK, TyrB)).

Ulrey et al. (2014) observed differences in protein expression in *P. aeruginosa* cells treated with cranberry proanthocyanidins. Up-regulated proteins included proteins involved in cation transportation (PchD, PvdN, PhuS) or amino-acid synthesis (PA0335, PA2044, HutG), iron siderophores and proteins activated in response to stress (OsmC, SodM). Down-regulation was observed in the case of proteins involved in ATP synthase, cytochrome c (PA2482), protein PA2481, proteins involved in DNA and RNA synthesis (TopA, RplC, Mfd) and citric acid cycle proteins (subunits of acetyl-CoA carboxylase and fumarase). Zhang and Rock (2004) demonstrated the role of EGCG and related plant polyphenols in inhibiting fatty acid synthesis. Phenolic compounds were found to inhibit fatty acid elongation, influencing FabG (NADPH-dependent ketoreductase) and FabI (NADH-dependent enoyl reductase) enzymes. The $IC_{50}$ values were in the range of 5–15 μM. The presence of a galloyl group was essential for inhibiting the activity of catechins. FabI activity was inhibited by EGCG binding to this enzyme, preventing it from binding to the nucleotide cofactor (NADH). The EGCG was able to bind to the free enzyme FabG, as well as to the FabG-NADPH complex, preventing the substrate from binding to the enzyme.

Polyphenols can also interact with bacteria cells by inhibiting DNA synthesis, which is associated with the inhibition of DNA gyrase (Wu, He, et al. 2013b; Plaper et al. 2003). This enzyme is responsible for introducing negative supercoils into DNA. Gyrase is composed of two A (gyrase A) and two B subunits (gyrase B). Subunit A catalyzes DNA breakage, while subunit B catalyzes ATP hydrolysis, which is essential for DNA supercoiling. Both subunits may be targets for antimicrobial agents. However, studies have shown that polyphenols are able to inhibit enzyme activity by binding to gyrase B (ATP binding site) (Gradišar et al. 2007; Plaper et al. 2003). To our knowledge, there is no data concerning the interaction of polyphenols with gyrase A. In a study by Wu, He, et al. (2013b), all the analyzed flavonoids showed the ability to inhibit *E. coli* DNA gyrase. However, kaempferol was the most active ($IC_{50} = 0.037$ mg/mL). Nobiletin was reported as having the lowest activity ($IC_{50} = 1.89$ mg/mL).

ATP synthase is crucial for energy production in the cells of animals, plants and microorganisms. Dadi, Ahmad, and Ahmad (2009) demonstrated that polyphenolic compounds (resveratrol, piceatannol, quercetin, quercetrin and quercetin-3-$\beta$-D glucoside) are able to inhibit ATPase activity and ATP synthase in *E. coli*. Piceatannol (~100% inhibited; $IC_{50}$~14 μM) showed the highest, complete inhibition activity against ATPase, followed by quercetin (~80%; $IC_{50}$~33 μM), quercetin-3-$\beta$-D-glucoside (~50%; $IC_{50}$~71 μM), resveratrol (~40%; $IC_{50}$~94 μM) and quercetrin (~40%; $IC_{50}$~120 μM). Stilbenes – resveratrol and piceatannol – suppressed ATPase and ATP synthesis, while the other compounds only inhibited enzyme activity. Chinnam et al. (2010) confirmed the inhibitory effect of polyphenols against *E. coli* ATP synthase, reporting effects from the strongest to weakest for morin ($IC_{50}$~0.07 mM)>silymarin ($IC_{50}$~0.11 mM)>baicalein ($IC_{50}$~0.29 mM)>silibinin ($IC_{50}$~0.34 mM)>rimantadin ($IC_{50}$~2.0 mM)>amantidin ($IC_{50}$~2.5 mM)>epicatechin ($IC_{50}$~4.0 mM). Hesperidin, chrysin, kaempferol, diosmin, apigenin, genistein and rutin showed degrees of inhibition in the range of 40–60%, while for galangin, daidzein and luteolin inhibition was insignificant.

Polyphenols also influence biofilm formation, but the effect is ambiguous. They can stimulate or inhibit biofilm formation depending on the concentration of polyphenolic compounds. Some studies demonstrated that at lower concentrations polyphenols have a stimulatory effect, while at higher concentrations they show an inhibitory effect. Quorum sensing, motility and adherence structures play important roles in biofilm formation and can be also be influenced by polyphenols. Ulrey et al. (2014) found that cranberry proanthocyanindins reduced the swarming motility of *P. aeruginosa*. Phenolics also influenced biofilm formation. At low concentrations of 1 μg/mL the degree of inhibition was 40.9%, while at a concentration of 10 μg/mL it was 55.7%. Moreover, confocal microscopy revealed that a biofilm treated with proanthocyanidins (10 μg/mL) decreased by between ~26 μm and ~20 μm. Biofilm density was also reduced. Polyphenols were not observed to have any effect on the adhesion ability of *P. aeruginosa*, probably due to the lack of adhesion to P-fimbriae.

Zhang et al. (2014) report that extract from *Rosa rugosa* tea significantly inhibits quorum sensing, by decreasing violacein production (87.56%) in *Chromobacterium violaceum*. Proanthocyanindins also reduced swarming motility in *E. coli* (84.90%) and *P. aeruginosa* (78.03%). The mass of *E. coli* and *P. aeruginosa* biofilm was reduced by about 67.02%

and 72.90%, in each respective case, but the *Rosa rugosa* tea extract did not influence bacteria growth. Plyuta et al. (2013) studied the effects of several phenolic compounds (4-hydroxybenzoic acid, vanillin, gallic acid, ferulic acid, sinapic acid, cinnamic acid, EC and chlorogenic acid) on biofilm formation by *P. aeruginosa*. It was found that the polyphenols had either an inhibitory or a stimulating effect, depending on the polyphenol concentration. At lower concentrations, which did not or only weakly inhibited bacteria growth, the compounds enhanced biofilm formation. The strongest effects were observed for vanillin and epicatechin, which increased biofilm formation 3-fold to 7-fold, whereas other polyphenols stimulated the biofilms 2-fold to 2.5-fold. At higher concentrations, the phenolics suppressed biofilm formation. A similar pattern was observed for the production of N-acyl-homoserine lactones, which stimulated biofilm formation. At concentrations of 40–400 µg/mL, 4-hydroxybenzoic, gallic acids and vanillin enhanced the production of these signal molecules, while higher concentrations had an inhibitory effect. Lower concentrations did not influence either swarming or twitching motility. However, higher concentrations decreased motility zones. Vanillin (400–800 µg/mL) decreased the size of the swarming motility zone by 50–60%, whereas twitching motility was decreased by 10–15% in the presence of 4-hydroxybenzoic acid, vanillin and gallic acid (400–800 µg/mL).

Antolak et al. (2017) demonstrated the antiadhesive properties of elderberry, lingonberry and cornelian cherry fruit juices against the beverage-spoiling bacteria *Asaia* spp. to various abiotic substances such as: glass, polystyrene and PET. It was also shown that cornelian cherry juice caused reduction in bacteria viability, whereas lingonberry and elderberry juices caused changes in the biofilm structure and micro-colonies were observed. Oliveira et al. (2017) report that acerola extract inhibited the production of violacein in *Chromobacterium violaceum* cells, but no influence was observed on the growth of bacteria. Higher concentrations (116.97 – 233.95 $mg_{GAE}$/L) inhibited violacein production, with values approaching those for furanone, which is a well-known quorum sensing inhibitor. The acerola extract did not inhibit the swarming motility of *Serratia marcescens* or the production of prodigiosin pigment. However, significant inhibition of biofilm formation by *C. violaceum, A. hydrophila* and *S. marcescens* strains was observed at all the studied concentrations (29.24–233.95 $mg_{GAE}$/L).

Pellegrini and Ponce (2019) report that extracts obtained from beet and leek leaves show anti-quorum sensing activity decreasing violacein production in at least 50%. No effect on the viability of bacteria cells was observed. The leek extract was more effective causing a decrease of around 80% in the production of the pigment at a concentration of 53.75 mg/mL. In addition, only leek extract showed anti-biofilm activity at concentration of 268.75 mg/mL.

The antibacterial action of polyphenols has many possible mechanisms. Polyphenols can cause morphological changes in bacteria cells and damage bacteria cell walls, including both the inner membrane and outer membrane, resulting in the leakage of intracellular components. Changes in cell shape, irregular forms, wrinkles on the surfaces of bacteria and the formation of cell aggregates may be observed Although the literature suggests that Gram-positive bacteria are generally more sensitive to polyphenols, the lipid bilayer of Gram-negative bacteria can also be permeable to antioxidants. Cell wall damage is associated with the prooxidant properties of polyphenols, which cause oxidative stress. The antibacterial activity of phenolic compounds is strictly related to their chemical structure, including the position and number of hydroxyl or methoxyl groups, as well as to the presence of galloyl groups in the catechin structure.

Moreover, polyphenols can influence protein biosynthesis and change metabolic processes in bacteria cells. They have been reported to inhibit DNA synthesis by suppressing gyrase activity, as well as to inhibit ATP synthesis. Finally, polyphenols can weaken the ability of microorganisms to survive, inhibiting biofilm formation including by suppressing quorum sensing and bacteria motility. Polyphenols can influence biofilm formation without inhibiting the growth and viability of bacteria. The influence of polyphenols on biofilm formation is related to the concentration. At higher concentrations, polyphenols can have inhibitory effect, while at lower concentrations they can have a stimulatory effect. Polyphenols can affect biofilm formation by influencing the quorum sensing mechanism, pigment production and bacteria swarming motility, or by changing the biofilm structure. The quorum sensing mechanism also depends on the concentration of polyphenols. The production of signal molecules is inhibited at higher concentrations but stimulated at lower concentrations.

## Effect of polyphenolic extracts on the microbial quality of meat and meat products

The purpose of meat processing such as salting, smoking, curing and fermentation is to improve the sensory properties of meat and extend its shelf life. However, meat processing (especially curing and smoking, which involve high temperatures) leads to the formation of highly carcinogenic compounds, such as N-nitroso-compounds, polycyclic aromatic hydrocarbons and heterocyclic aromatic amines. The International Agency for Research on Cancer (IARC) warns that processed meat can increase the risk of colorectal cancer. Eating 50 g of processed meat per day increases the risk of colorectal cancer by 18% (Bouvard et al. 2015). Therefore, new natural and safer methods of preserving meat products are sought as alternatives to nitrates (III). Due to their antioxidant and antimicrobial properties, plant extracts rich in polyphenolic compounds seem a promising solution (Alahakoon et al. 2015). Table 3 presents examples of the use of plant extracts rich in polyphenols as natural preservatives for meat and meat products.

Herbs and spices are commonly used as food additives to enhance their sensory characteristics. However, they are also effective at extending the shelf life of food products. Biswas, Chatli, and Sahoo (2012) investigated the effects of curry (*Murraya koenigii* L.) and mint (*Mentha spicata*) leaf extracts on the stability of raw ground pork meat during

refrigerated storage. Ethanol extract of curry leaves and water extract of mint leaves were used, since these had the highest antioxidant potential. During storage, the pH increased but samples containing the plant extracts showed lower pH values compared to a control sample with salt. The extracts also prevented oxidative changes in the meat and the TBARS values were significantly lower in the samples treated with mint, curry and sodium nitrate (III) compared to the control. The strongest effect was observed for curry extract.

Fernandes et al. (2016) evaluated the influence of oregano extract on the level of microorganisms in sheep burgers stored in MAP. Oregano extract slightly improved the microbial quality of the meat products. Although microbial counts increased during refrigerated storage, after 20 days samples treated with oregano (8.95 log CFU/g) and BHT (8.69 log CFU/g) showed similar TVC levels, which were lower than for the control (9.11 CFU/g). A similar pattern was observed for LAB counts. Burgers containing oregano (6.14 log CFU/g) and BHT (6.09 log CFU/g) showed significantly lower LAB levels in comparison to the control (7.82 log CFU/g). The extract also improved the color stability of the meat. The L* values in samples with oregano and BHT were similar and stable during storage, while an increase was observed in the case of the control. A decrease in redness was observed for all treatments but after 10 days samples treated with BHT or oregano showed significantly higher a* values, suggesting lower myoglobin oxidation. Moreover, oregano and BHT inhibited lipid and protein oxidation, by about 40–50% and 20–30%, respectively, after 20 days compared to the control. No differences between the treatments were observed in terms of the fatty acid profile during storage. However, analysis of volatile compounds, especially lipid-derived compounds, revealed some differences and after 20 days the total amount of volatile compounds was significantly lower in the sample treated with BHT than in the sample with oregano. Moreover, the oregano extract prevented sensory changes (red-color, surface discoloration, off-odor) for 15 days, after which it slightly improved the sensory attributes of the meat compared to the control.

Shan et al. (2009) investigated the use of cinnamon stick, oregano, cloves, pomegranate peel and grape seed extracts as natural preservatives for pork meat packed aerobically and stored at 20 °C. Their antibacterial activity was tested against foodborne pathogens (*L. monocytogenes, S. enterica, S. aureus*). All the extracts inhibited the growth of the tested bacteria. However, the cloves and cinnamon stick extracts were the most active. Gram-positive strains were more susceptible than Gram-negative. All the herbs and spices decreased the pH values of the samples compared to the control. After 9 days, the pH ranged from 6.07 to 6.19, while the pH of the control was 6.82. The extracts also improved the color stability of the pork meat. During storage, L*, a*, b* and H* values did not change as significantly as in the control, suggesting that the herbs and spices had a protective effect. However, all the samples treated with extracts, except for cinnamon stick, revealed lower redness (a*) than the control. A significant antioxidant effect, expressed as the level of lipid oxidation, was observed. After 9 days of storage, the TBARS values increased by 21–28%, while those for the control increased by more than 3000%.

Radha Krishnan et al. (2014) studied the effect of dried cloves, cinnamon, oregano and mustard, individually and in combinations, on the shelf life of raw chicken meat. The extracts significantly reduced pH values in comparison with a negative control and a positive control (containing BHT). The lowest pH was detected for chicken meat containing a combination of cloves, cinnamon and oregano (pH = 5.13). With other treatments, the pH at the end of storage ranged from 5.22 to 5.73. In the control samples, pH values increased from 5.63 to 6.69 (negative control) and from 5.63 to 6.32 (positive control). This may have been due to the growth of bacteria, which metabolized amino acids released during the breakdown of proteins. The spices also had a significant influence on the color parameters of raw chicken meat during refrigerated storage. The lightness (L*) values increased during storage, whereas a decrease was observed in the control samples. The L* values were higher in samples containing the extracts than in the controls. The redness of meat samples with extracts was higher compared to the controls, probably due to the content of carotenoids. During the storage period, a* values decreased. Yellowness (b*) values increased with all treatments compared to the controls. The spice extracts significantly affected the microbial quality of the raw chicken meat and inhibited bacteria growth. The TVC, LAB, *Enterobacteriaceae* and *Pseudomonas* sp. counts were lower in meat samples treated with the extracts compared to the controls. However, mixed spice extracts had stronger antibacterial effects than individual spices. After 15 days, the TVC of the control samples increased from 5.39 to 7.15 (negative control) and 7.04 (positive control) $\log_{10}$ CFU/g, while in samples treated with the spices it reached 5.79 (clove), 5.95 (cinnamon), 5.85 (oregano) and 6.35 (mustard) log10 CFU/g. The lowest TVC was detected for a combination of clove, cinnamon and oregano (5.5 $\log_{10}$ CFU/g). The spice extracts contributed to reduce lipid oxidation and the strongest antioxidant effects were shown by mixtures of spices. The extracts significantly improved the sensory properties of the chicken meat. In the control samples, a lower acceptability score of 6.0 for odor was obtained after 6 days for the control samples whereas for the samples treated with spice extracts the same score was reached after 12 days.

Casaburi et al. (2015) investigated the antimicrobial properties of *Myrtus communis* leaf extract in ground beef. The extract decreased TVC, the amount of *B. thermospacta*, lactic acid bacteria and *Enterobacteriacea,* but did not have a significant influence on *Pseudomonas fragi.* Myrtle extract was the most active against *B. thermosphacta*. Interestingly, in vitro myrtle extract revealed antibacterial activity against *B. thermosphacta* as well as *P. fragi,* although the strains of *Pseudomonas* sp. were less sensitive. Therefore, the activity of myrtle extract was lower in situ than in vitro and higher concentrations should be used in meat products. The activity of various compounds could be lower in complex matrices due to intrinsic properties of food. Some factors such as

**Table 3.** Application of plant extracts in meat and meat products.

| Plant material | Scientific name | Extraction solvent | Type of meat/ meat products | Storage conditions | Storage time | Parameters studied | Reference |
|---|---|---|---|---|---|---|---|
| Curry leaves<br>Mint leaves | *Murraya koenigii*<br>*Mentha spicata* | Ethanol<br>Water | Raw ground pork meat | Aerobically packed in low density polyethylene bags, 4 ± 1 °C | 12 days | Oxidative stability (TBA), instrumental color values (Hunter L, a, b), pH | Biswas, Chatli, and Sahoo (2012) |
| Oregano | *Origanum vulgare* | Acetone/water/glacial acetic acid (70/28/ 2% v/v/v) | Sheep burgers | MAP (80% O2 +, 20% CO2), 2 ± 1 °C | 20 days | Microbial count (TVC, LAB, *Enterobacteriacea, Pseudomonas* counts), pH, lipid oxidation (TBA), protein oxidation, instrumental color values (CIE L*a*b*), free fatty acid profile, volatile compounds profile, sensory properties | Fernandes et al. (2016) |
| Cinnamon stick<br><br>Oregano leaves<br><br>Clove buds<br>Pomegranatepeel<br>Grape seed | *Cinnamomum burmannii,*<br><br>*Origanum vulgare*<br><br>*Eugenia caryophylata,*<br>*Punica granatum*<br>*Vitis vinifera* | Ethanol | Raw pork meat | Aerobically packed, 20 °C | 9 days | Antibacterial activity in meat *against L. monocytogenes, S. enterica, S. aureus,* pH, instrumental color values (L*, a*, b*, H*), lipid oxidation (TBA) | Shan et al. (2009) |
| Clove<br>Cinnamon,<br>Oregano<br>Mustard | *Syzygium aromaticum*<br>*Cinnmomum cassia*<br>*Origanum vulgare*<br>*Brassica nigra* | Water | Raw chicken meat | Aerobically packed in low density polyethylene bags, 4 °C | 15 days | pH, microbial count (TVC, LAB, *Enterobacteriaceae, Pseudomonas* counts), lipid oxidation (TBA), instrumental color values (CIE L*, a*, b*), sensory properties (taste, odor) | Radha Krishnan et al. (2014) |
| Myrtle leaves | *Myrtus communis* | Ethanol/water (70/30 % v/v) | Ground beef | 4 °C | 5 days | Microbial count (TVC, *Pseudomonas* sp., *B. thermosphacta*, LAB, *Enterobacteriacea*e counts) | Casaburi et al. (2015) |
| Sour cherry leaves<br>Black currant leaves | *Prunus cerasus*<br>*Ribes nigrum* | Water | Pork sausages (cooked and smoked) | Vacuum packed, 4 ± 2° C | 28 days | Microbial count (TVC, (PC, *Enterobacteriaceae, Pseudomonas* sp., *B. thermosphacta* counts), community level physiological profiling (CLPP): metabolic activity of microorganisms | Nowak et al. (2016) |

(*continued*)

**Table 3.** Continued.

| Plant material | Scientific name | Extraction solvent | Type of meat/ meat products | Storage conditions | Storage time | Parameters studied | Reference |
|---|---|---|---|---|---|---|---|
| | | | | | | (AWCD) microbial population diversity (Shannon-Weaver index), lipid oxidation (TBA), instrumental color values (CIE L*a*b*), sensory properties (taste, odor, color) | |
| Cocoa leaves | *Theobroma cacao* | Ethanol | Mechanically deboned chicken meat | air, 4.00 ± 0.1 °C | 4 weeks | Peroxide value, lipid oxidation (TBA), headspace analysis (GC) | Hassan and Fan (2005) |
| Olive leaves | *Olea europaea* L. var. Chemlali North | methanol/water (4:1 v/v) | Raw and cooked minced beef meat | Packed in alluminium foil, 4 °C | 12 days | pH, storage loss, defrosting loss, cooking loss, Napole technological yield, metmyoglobin formation, lipid oxidation (TBA), sensory properties | Aouidi, Okba, and Hamdi (2017) |
| – | *Syzygium antisepticum* | Acetone:methanol:water (2:2:1 v/v/v) | Cooked chicken | Air-packaged, 4, 10, 25 °C | 5 days (4and 10 °C) or 24 hours (25 °C) | Microbial count (S. aureus, MRSA), instrumental color values (CIE L*a*b*) | Yuan and Yuk (2018) |
| Cherry powder extract | *Prunus cerasus* cv Montmorency | Water | Ground pork patties | Vacuum packed, 4 ± 2° C | 8 days | Antioxidant capacity (ABTS), lipid oxidation (TBA), instrumental color values (L*,a*,b*), fatty acids profile, volatile compounds profile, TVC, sensory properties (appearence, color, taste, flavor, juiciness, texture, overall acceptability) | Brodowska et al. (2017) |
| Black currant fruits | *Ribes nigrum* | 40% ethanol | Raw pork patties | Polypropylene trays, overwrapped with an oxygen-permeable polyvinyl chloride film, 4° C | 9 days | Lipid oxidation (TBA), protein oxidation (carbonyl content, sulfhydryl content), instrumental color values (L*, a*) | Jia et al. (2012) |
| Grape seeds<br>Green tea leaves<br>Seaweed<br><br>Chestnut leaves | *Vitis vinifera,*<br>*Camellia sinensis*<br>*Ulva lactuca* and *Ulva rigida*<br>*Castanea sativa* | ethanol/ water (1/1 v/v)<br>70% ethanol<br>1.5% $H_2SO_4$<br>water + 0.1 M HCl | Ground meat patties | MAP (80% $O_2$ + 20% $CO_2$) | 20 days | Microbial count (TVC, PC, LAB, *Pseudomonas*, pH, instrumental color values (Cie L*a*b*), lipid oxidation (TBA), | Lorenzo et al. (2014) |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Grape pomace | *Vitis vinifera* (Emir, Gamay, Kalecik Karasi, Narince, Okuzgozu varieties) | ethanol/water (95/5 v/v) | Beef patties | 4 ± 1 °C | 48 hours | Microbial count (TVC, PC, *Enterobacteriaceae*, coliform bacteria, *Salmonella* sp., enterococci, *S. aureus*, lipolytic bacteria, *Micrococcaceae*, lactobacilli, lactococci, yeasts and molds) | Sagdic et al. (2011) |
| Rose | *Rosa* | water | Naturally dry fermented pork sausages | 20 °C and 90% relative humidity (RH) - 3 days, 10 °C and 80% RH - 5 days, 10 °C and 70% RH - 16 days | 24 days | Water activity, moisture, pH, lipid oxidation (TBA), biogenic amines formation (histamine, putrescine, cadaverine, phenylethylamine, tryptamine, tyramine, spermidine, and spermine), microbial count (TVC, LAB counts), bacteria diversity (16S rRNA gene sequencing) | Zhang et al. (2017) |
| Green tea<br>Grape seed | *Camellia sinensis*<br>*Vitis vinifera* | – | Dry cured bacons (with sodium nitrite) | Vacuum packed, 4 °C | 3 weeks | Moisture, residual, sodium nitrite contents, lipid oxidation (TBA), microbial count (TVC, *Enterobacteriacea* counts), biogenic amines formation (cadaverine, spermine, tyramine, putrescine, histamine), N-nitrosoamines formation, sensory evaluation | Wang et al. (2015) |

storage temperature, packaging conditions and type of microorganisms can influence bacterial activity. Moreover, environmental strains are often more resistant to antibacterial agents than collection cultures.

Yuan and Yuk (2018) investigated the antibacterial activity of *Syzygium antisepticum* extract in cooked chicken against *S. aureus*, including the MRSA strain, during storage at 4, 10 and 25 °C. At 4 °C after 5 days at concentrations of 2 or 8 mg/mL, the extract did not influence microbial count, while treatment with 32 mg/mL extract resulted in a small but significant decrease in *S. aureus* (3.5. log CFU/g) and MRSA (3.9 log CFU/g) counts. At 10 °C, the extract at concentration of 32 mg/mL caused significant reduction in bacteria count and after 5 days the level of microorganisms reached 3.9 log CFU/g (*S. aureus*) and 4.0 log CFU/g (MRSA). At 25 °C, treatment with 8 mg/mL extract resulted in a slower bacteria growth, with final cell count of 7.3 log CFU/g (*S. aureus*) and 7.6 log CFU/g (MRSA). At a concentration of 32 mg/mL the extract inhibited microbial growth in cooked chicken for up to 16 h in the case of *S. aureus* (4.5 log CFU/g) and for up to 8 h with MRSA (4.9 log CFU/g). The addition of *S. antisepticum* extract, particularly at a concentration of 32 mg/mL, significantly reduced L*values, increased b* values and decreased a* values compared to the control.

Brodowska et al. (2017) studied the activity of cherry powder extract at concentrations of 20 $mg_{GAE}$/kg and 40 $mg_{GAE}$/kg in raw pork patties. Using the ABTS method, it was found that meat samples with cherry extract maintained high antioxidant activity during storage. At the end of the storage period (day 8), at a concentration of 40$mg_{GAE}$/kg the extract showed almost double the antioxidant capacity compared to that in the control. The TBARS values remained lower than those for the control over the whole storage time. No changes in the fatty acids profile caused by oxidation were observed, indicating that the polyphenolic extracts had a protective effect. The addition of cherry extract also prevented the loss of redness and decreased lightness compared to the control. Cherry extract (40 $mg_{GAE}$/kg) improved the sensory attributes of pork patties and enhanced their overall acceptability, taste and flavor. It was not found to influence aerobic bacteria counts.

Jia et al. (2012) studied the antioxidant efficacy of black currant extract in raw pork patties. Lipid oxidation was significantly inhibited. After 9 days of storage, the addition of 5, 10 and 20 g/kg of the extract significantly decreased TBARS values, by 74.9, 90.6 and 91.7%, respectively, compared to the control. Moreover, treatment with 10 and 20 g/kgs had a similar effect as 0.2 g/kg BHA. The black currant extract also inhibited protein oxidation. Patties treated with 5 g/kg of the extract and BHA showed an insignificant decrease in carbonyl content, whereas with 10 and 20 g/kg an inhibitory effect was noticed after 6 and 9 days of storage, respectively. The addition of the extracts inhibited the loss of sulfhydryl groups, released during protein oxidation. However, using 5 and 10 g/kg concentrations resulted in stronger antioxidant capacity than for BHA and higher concentrations of extract. The authors suggest that polyphenols could interact with sulfhydryl groups. Black currant fruits, due to their high content of anthocyanins, significantly enhanced the redness of pork patties and decreased their lightness.

The leaves of fruit trees and shrubs are generally considered waste products and are not applied in the food industry. Given their high content of polyphenolic compounds, leaves are a promising material for natural extracts and could be added to meat and meat products as natural preservatives. Nowak et al. (2016) produced pork sausages with extracts obtained from sour cherry and black currant leaves. Both extracts showed strong antioxidant effects and significantly reduced lipid oxidation compared to a control sample with salt (nitrates (III)>black currant leaves extract > sour cherry leaves extract > salt). However, the extracts did not enhance the color parameters of the sausages during refrigerated storage. At the end of storage (28 days), the sausages with sour cherry and black currant extracts showed higher L* values than sausage with nitrates (III) and similar values to the control sausage with salt. Unfortunately, the use of plant extracts did not provide the red color characteristic of pork meat products cured with salt.

The leaf extracts had a positive effect on the microbial quality of vacuum-packed sausages. Levels of TVC, PC, LAB, *Pseudomonas* sp., *B. thermosphacta* and *Enterobacteriaceae* increased during storage in all samples, but the increase was greatest in the control sausage with salt. Principal component analysis revealed that after 14 days the control sausage with salt showed microbial quality similar to that of samples treated otherwise at day 28. After 28 days, the control sample was separated from the other meat products. The extracts stabilized the microbial counts in the meat products over 14 days of storage. After 28 days, the extracts only inhibited the growth of *Pseudomonas* sp. The metabolic activity of the microorganisms (AWCD index) decreased during storage in sausage containing curing salt and plant extracts, whereas it increased in the control. The diversity of the microbial population (Shannon-Weaver index) in the sample with cherry extract was comparable to that for the sample with curing salt and significantly lower than in other treatments. The addition of leaf extracts did not have a negative influence on the sensory attributes of the pork sausages.

Hassan and Fan (2005) studied the possibility of using cocoa leaf extract as a natural antioxidant in mechanically deboned chicken meat. The peroxide value, describing fat oxidation, showed that at lower concentrations (200 and 200 mg/kg) cocoa leaf extracts were not as efficient as green tea extract or BHA/BHT, although at higher concentrations (400 and 800 mg/kg) their antioxidant activity was comparable. Similar results were obtained using the TBA method. Headspace analysis revealed that all the cocoa leaf extracts reduced the formation of hexanal in the chicken meat compared to the control. The concentrations of hexanal in the samples treated with BHA/BHT, green tea extract and cocoa leaf extract (800 mg/kg) were similar.

Aouidi, Okba, and Hamdi (2017) added olive leaf extract to raw and cooked minced beef meat. During refrigerated

storage, the pH of the control samples decreased by 1.3 units, while the extract caused a slight increase in pH, of 0.13–0.68 units. The extract also reduced the formation of metmyoglobin and inhibited browning. After 12 days of storage, the metmyoglobin content increased by 65% and 43% in the raw and cooked control samples, respectively, while in the samples treated with extract it increased by 21–43% (raw meat) and 14–25% (cooked meat), depending on the extract form and concentration. Olive leaf polyphenols reduced lipid oxidation by 25–65% compared to the control. The technological quality of the meat was also improved by lower storage and defrosting losses, without influencing cooking loss or Napole yield. No influence on sensory properties was reported.

Lorenzo et al. (2014) used tea, grape, seaweed and chestnut extracts as natural preservatives for ground pork patties. The extracts differed in terms of antibacterial activity. The tea, grape extracts and BHT were associated with lower TVC in the pork patties compared to the control, whereas with seaweed and chestnut TVC values increased. The control patties reached the spoilage limit of $10^6$ CFU/g after 13 days of storage, while tea extract extended the shelf life to 20 days. *Pseudomonas* sp., LAB and PC were also inhibited by the tea and grape extracts. Patties treated with seaweed and chestnut extracts showed higher levels of LAB and PC than the control. The tea, grape and seaweed extracts caused a decrease in the pH of porcine patties, while with the chestnut extract the pH increased. These differences in pH could be a result of polyphenolic composition. The grape extract, containing gallic acid, protocatechuic acid and galloylated proanthocyanidins, was the most acidic, whereas the chestnut extract did not contain compounds with acidic groups. An increase in lightness and yellowness during storage was noticed for the patties with plant extracts, whereas there was no such increase for the control. The L* values were higher than in the control and grape extract improved the redness of the meat products.

Wang et al. (2015) investigated the effect of green tea and grape seed polyphenols on the quality of dry-cured bacon during ripening and storage. The bacon also contained nitrates (III). The extracts significantly decreased the pH values of the bacon. However, only green tea extract showed an antioxidant effect, reducing TBARS values. The plant extracts also reduced the residual nitrites in the bacon. After 3 weeks of storage, the TVC values in samples treated with grape tea and grape tea + grape seed extracts were 5.37 and 5.72 log CFU/g, respectively, which means that they were not considered spoilt. The amount of *Enterobacteriacea* was significantly lower in the bacon treated with plant extracts. All the extracts inhibited the formation of biogenic amines (cadaverine, spermine, tyramine, putrescine and histamine), as well as the formation of nitrosoamines. The activity of the plant additives was in the following order: green tea > green tea + grape seed > grape seed. Principal component analysis indicated positive correlations between physicochemical factors (moisture and residual sodium nitrite contents), biogenic amines (putrescine, cadaverine, histamine, tyramine and spermine), nitrosoamines and TVC, as well as between the TBARS and sodium nitrate (III). A negative correlation was observed between nitrosoamines and nitrates (III).

Sagdic et al. (2011) report that grape pomace extract may improve the microbial quality of beef patties. Five grape varieties were tested. At a concentration of 10%, all the extracts inhibited the growth of the tested microorganisms (TVC, PC, *Enterobacteriaceae*, coliform bacteria, *S. aureus*, lipolytic bacteria, *Micrococcaceae*, lactobacilli, lactococci, yeasts and molds). However, Emir, Gamay and Kalecik Karasi varieties containing higher quantities of polyphenols showed better antimicrobial properties. At a concentration of 5%, they inhibited pathogenic foodborne bacteria including *Enterobacteriaceae*, as well as coliform bacteria, spoilage microorganisms including yeasts, molds and lipolytic bacteria.

Zhang et al. (2017) evaluated the effect of rose polyphenols on the stability of naturally dry fermented sausages. Rose polyphenols inhibited the increase in pH values and decreased TBARS values. Rose extract also contributed to the reduction of the formation of biogenic amines (phenylethylamine, spermidine, cadaverine, tyramine, histamine, putrescine), which are the indicators of microbial spoilage processes. Rose polyphenols decreased TVC from day 14 to day 24 of storage. However, it increased the amount of lactic acid bacteria from day 0 to day 10 of storage. 16S rRNA gene sequencing indicated that the bacteria community was more diverse in the control than in the sausages supplemented with polyphenols. The predominant species in all the samples were *Pseudomonas* sp., *Psychrobacter* sp., *Acinetobacter* sp., *Staphylococcus* sp. and *Kocuria* sp. The rose polyphenols increased the richness of *Lactobacillales*.

Polyphenols are strong antioxidants, which are very effective at improving the oxidative stability of meat and meat products. They inhibit the oxidation of meat ingredients such as lipids and proteins, sometimes with higher intensity than chemical antioxidants. Polyphenols also protect from discoloration during storage, by inhibiting myoglobin conversions. Extracts obtained from fruits such as grapes and black currants or spices usually influence the color of meat. This is related to the content of color compounds, mainly anthocyanins and carotenoids. Plant extracts can improve the color of meat compared to controls, giving a pink-red color. Extracts can also suppress the formation of biogenic amines and improve the microbial quality of meat, inhibiting the growth of spoilage microorganisms and improving microbial quality of meat and meat products.

## Summary

Plants are a rich source of bioactive compounds, especially polyphenols. These compounds show strong biological activity, acting as antioxidants and antimicrobial agents. Polyphenolic extracts inhibit growth of spoilage microorganisms and foodborne pathogens, but Gram-negative bacteria are generally more resistant to polyphenolic compounds. Plant extracts rich in polyphenols offer a promising alternative to the chemical

preservatives used in the meat industry. When applied in meat or meat products, they inhibit the growth of microorganisms, oxidation of meat ingredients, prevent from discoloration or improve meat color.

The exact mechanism that controls the antibacterial activity of polyphenols is still not well understood. There are several possible mechanisms of action, which include cell wall damage resulting in leakage of intracellular components, morphological changes and inducing ROS formation which leads to oxidative stress in bacteria cells. Polyphenols can also influence protein biosynthesis and change metabolic processes in bacteria cells, inhibit DNA synthesis by suppressing gyrase activity, inhibit ATP synthesis and influence biofilm formation. Plant extracts are mixtures of polyphenols as well as other bioactive compounds, so interactions between them may influence the activity of the whole extract. There are many other factors too which influence the polyphenolic composition of plants and their extracts, such as the plant variety/cultivar, the part of the plant, the growth season, particle size of plant material and the extraction method. Further research is required into the antibacterial activity of plant extracts and their possible uses in meat/meat products.

## Abbreviations

| | |
|---|---|
| ABTS | 2,2′-azino-bis(3-ethylbenzothiazoline-6-sulphonic acid) |
| AFM | atomic force microscopy |
| AWCD | average well color development |
| BHA | 2-tert-Butyl-4-hydroxyanisole and 3-tert-butyl-4-hydroxyanisole |
| BHT | 2,6-bis(1,1-dimethylethyl)-4-methylphenol |
| CAE | chlorogenic acid equivalents |
| CG | catechin gallate |
| CFU | colony forming unit |
| DPPH | 2,2-diphenyl-1-picrylhydrazyl |
| DW | dry weight |
| EC | epicatechin |
| ECG | epicatechin gallate |
| EGC | epigallocatechin |
| EGCG | epigallocatechin gallate |
| FW | fresh weight |
| GA | gallic acid |
| IZ | inhibition zone |
| LAB | lactic acid bacteria |
| MALDI-TOF/TOF MS | matrix assisted laser desorption/ionization - time of flight mass spectrometry |
| MBC | minimum bactericidal concentration |
| MAP | modified atmosphere packaging |
| MIC | minimum inhibitory concentration |
| MRSA | methicillin-resistant *Staphylococcus aureus* |
| MSSA | methicillin-susceptible *Staphylococcus aureus* |
| PC | psychrotrophic count |
| ROS | reactive oxygen species |
| SEM | scanning electron microscopy |
| TBARS | thiobarbituric acid reactive substances |
| TE | Trolox equivalents |
| TEM | transmission electron microscopy |
| TPC | total phenolic count |
| TVC | total viable count |
| QE | quercetin equivalents |

## References


Alahakoon, A. U., D. D. Jayasena, S. Ramachandra, and C. Jo. 2015. Alternatives to nitrite in processed meat: Up to date. *Trends in Food Science & Technology* 45 (1):37–49. doi: 10.1016/j.tifs.2015.05.008.

Antolak, H., A. Czyzowska, M. Sakač, A. Mišan, O. Đuragić, and D. Kregiel. 2017. Phenolic compounds contained in little-known wild fruits as antiadhesive agents against the beverage-spoiling bacteria Asaia spp. *Molecules* 22 (8):1256–18. doi: 10.3390/molecules22081256.

Aouidi, F., A. Okba, and M. Hamdi. 2017. Valorization of functional properties of extract and powder of olive leaves in raw and cooked minced beef meat. *Journal of the Science of Food and Agriculture* 97 (10):3195–203. doi: 10.1002/jsfa.8164.

Bancirova, M. 2010. Comparison of the antioxidant capacity and the antimicrobial activity of black and green tea. *Food Research International* 43 (5):1379–82. doi: 10.1016/j.foodres.2010.04.020.

Bastos, D. H., L. A. Saldanha, R. R. Catharino, A. Sawaya, I. B. Cunha, P. O. Carvalho, and M. N. Eberlin. 2007. Phenolic antioxidants identified by ESI-MS from yerba maté *(Ilex paraguariensis)* and green tea (*Camelia sinensis*) extracts. *Molecules* 12 (3):423–32. doi: 10.3390/12030423.

Bazzaz, B. S. F., S. Sarabandi, B. Khameneh, and H. Hosseinzadeh. 2016. Effect of catechins, green tea extract and methylxanthines in combination with gentamicin against *Staphylococcus aureus* and *Pseudomonas aeruginosa*:-combination therapy against resistant bacteria. *Journal of Pharmacopuncture* 19 (4):312–8. doi: 10.3831/KPI.2016.19.032.

Belkhir, M., O. Rebai, K. Dhaouadi, B. Sioud, M. Amri, and S. Fattouch. 2013. Antioxidant and antimicrobial activities of Tunisian azarole (*Crataegus azarolus* L.) leaves and fruit pulp/peel polyphenolic extracts. *International Journal of Food Properties* 16 (6):1380–93. doi: 10.1080/10942912.2011.586080.

Bhattacharya, D., D. Ghosh, S. Bhattacharya, S. Sarkar, P. Karmakar, H. Koley, and R. Gachhui. 2018. Antibacterial activity of polyphenolic fraction of Kombucha against *Vibrio cholerae*: Targeting cell membrane. *Letters in Applied Microbiology* 66 (2):145–52. doi: 10.1111/lam.12829.

Biswas, A. K., M. K. Chatli, and J. Sahoo. 2012. Antioxidant potential of curry (*Murraya koenigii* L.) and mint (*Mentha spicata*) leaf extracts and their effect on colour and oxidative stability of raw ground pork meat during refrigeration storage. *Food Chemistry* 133 (2):467–72. doi: 10.1016/j.foodchem.2012.01.073.

Borges, G., A. Degeneve, W. Mullen, and A. Crozier. 2010. Identification of flavonoid and phenolic antioxidants in black currants, blueberries, raspberries, red currants, and cranberries. *Journal of Agricultural and Food Chemistry* 58 (7):3901–9. doi: 10.1021/jf902263n.

Bouvard, V., D. Loomis, K. Z. Guyton, Y. Grosse, F. E. Ghissassi, L. Benbrahim-Tallaa, N. Guha, H. Mattock, and K. Straif. 2015. Carcinogenicity of consumption of red and processed meat. *The Lancet Oncology* 16 (16):1599–600. doi: 10.1016/S1470-2045(15)00444-1.

Brodowska, M., Guzek, D. Godziszewska, J. Górska-Horczyczak, E. Pogorzelska, E. Sakowska, A. Wojtasik-Kalinowska, I. Gantne, M. and A. Wierzbicka. 2017. Cherry *(Prunus cerasus* cv Montmorency) extract with standardised antioxidant potential as preservative for refrigerated storage of ground pork. *International Journal of Food Science & Technology* 52 (12):2555–63. doi: 10.1111/ijfs.13541.

Brudzynski, K., K. Abubaker, and D. Miotto. 2012. Unraveling a mechanism of honey antibacterial action: Polyphenol/H2O2-induced oxidative effect on bacterial cell growth and on DNA degradation. *Food Chemistry* 133 (2):329–36. doi: 10.1016/j.foodchem.2012.01.035.

Brudzynski, K., and R. Lannigan. 2012. Mechanism of honey bacteriostatic action against MRSA and VRE involves hydroxyl radicals generated from honey's hydrogen peroxide. *Frontiers in Microbiology* 3:1–8. doi: 10.3389/fmicb.2012.00036.

Cantwell, M., and C. Elliott. 2017. Nitrates, nitrites and nitrosamines from processed meat intake and colorectal cancer risk. *Journal of Clinical Nutrition & Dietics* 3 (4):27. doi: 10.4172/2472-1921.100061.

Cao, Y. D., Qian, H. L. C. M. Feng, T. Wang, T. Z. Y. Guo, X. K. Wu, and S. H. Zhang. 2019. Study on the Mechanism of Epigallocatechin Gallate (EGCG) to the Cell Membrane of *Escherichia coli*. *Science of Advanced Materials* 11 (2):262–8. doi: 10.1166/sam.2019.3458.

Casaburi, A., V. D. Martino, D. Ercolini, E. Parente, and F. Villani. 2015. Antimicrobial activity of *Myrtus communis* L. water-ethanol extract against meat spoilage strains of *Brochothrix thermosphacta* and *Pseudomonas fragiin vitro* and in meat. *Annals of Microbiology* 65 (2):841–50. doi: 10.1007/s13213-014-0925-9.

Cavaliere, C., P. Foglia, R. Gubbiotti, P. Sacchetti, R. Samperi, and A. Lagana. 2008. Rapid-resolution liquid chromatography/mass spectrometry for determination and quantitation of polyphenols in grape berries. *Rapid Communications in Mass Spectrometry* 22 (20): 3089–99. doi: 10.1002/rcm.3705.

Chinnam, N., P. K. Dadi, S. A. Sabri, M. Ahmad, M. A. Kabir, and Z. Ahmad. 2010. Dietary bioflavonoids inhibit *Escherichia coli* ATP synthase in a differential manner. *International Journal of Biological Macromolecules* 46 (5):478–86. doi: 10.1016/j.ijbiomac.2010.03.009.

Cho, Y. S., J. J. Oh, and K. H. Oh. 2010. Antimicrobial activity and biofilm formation inhibition of green tea polyphenols on human teeth. *Biotechnology and Bioprocess Engineering* 15 (2):359–64. doi: 10.1007/s12257-009-0195-8.

Cho, Y. S., N. L. Schiller, and K. H. Oh. 2008. Antibacterial effects of green tea polyphenols on clinical isolates of methicillin-resistant *Staphylococcus aureus*. *Current Microbiology* 57 (6):542–6. doi: 10.1007/s00284-008-9239-0.

Cho, Y. S., N. L. Schiller, H. Y. Kahng, and K. H. Oh. 2007. Cellular responses and proteomic analysis of *Escherichia* coli exposed to green tea polyphenols. *Current Microbiology* 55 (6):501–6. doi: 10.1007/s00284-007-9021-8.

Chrzanowski, G., B. Leszczyński, P. Czerniewicz, H. Sytykiewicz, H. Matok, R. Krzyżanowski, and C. Sempruch. 2012. Effect of phenolic acids from black currant, sour cherry and walnut on grain aphid (*Sitobion avenae* F.) development. *Crop Protection* 35:71–7. doi: 10.1016/j.cropro.2012.01.005.

Coman, M. M., A. M. Oancea, M. C. Verdenelli, C. Cecchini, G. E. Bahrim, C. Orpianesi, A. Cresci, and S. Silvi. 2017. Polyphenol content and in vitro evaluation of antioxidant, antimicrobial and prebiotic properties of red fruit extracts. *European Food Research and Technology* 244 (4):1–11. doi: 10.1007/s00217-017-2997-9.

Cory, H., S. Passarelli, J. Szeto, M. Tamez, and J. Mattei. 2018. The role of polyphenols in human health and food systems: A mini-review. *Frontiers in Nutrition* 5:1–9. doi: 10.3389/fnut.2018.00087.

Cui, Y., Y. J. Oh, J. Lim, M. Youn, I. Lee, H. K. Pak, W. Park, W. Jo, and S. Park. 2012. AFM study of the differential inhibitory effects of the green tea polyphenol (−)-epigallocatechin-3-gallate (EGCG) against Gram-positive and Gram-negative bacteria. *Food Microbiology* 29 (1):80–7. doi: 10.1016/j.fm.2011.08.019.

Dadi, P. K., M. Ahmad, and Z. Ahmad. 2009. Inhibition of ATPase activity of *Escherichia coli* ATP synthase by polyphenols. *International Journal of Biological Macromolecules* 45 (1):72–9. doi: 10.1016/j.ijbiomac.2009.04.004.

Daglia, M. 2012. Polyphenols as antimicrobial agents. *Current Opinion in Biotechnology* 23 (2):174–81. doi: 10.1016/j.copbio.2011.08.007.

Dent, M., V. Dragović-Uzelac, M. Penić, M. Brnčić, T. Bosiljkov, and B. Levaj. 2013. The effect of extraction solvents, temperature and time on the composition and mass fraction of polyphenols in Dalmatian wild sage (*Salvia officinalis* L.) extracts. *Food Technology and Biotechnology* 51 (1):84–91.

Dhiman, R., N. Aggarwal, K. R. Aneja, and M. Kaur. 2016. *In vitro* antimicrobial activity of spices and medicinal herbs against selected microbes associated with juices. *International Journal of Microbiology* 2016:1–9. doi: 10.1155/2016/9015802.

Dolan, A., C. M. Burgess, T. B. Barry, S. Fanning, and G. Duffy. 2009. A novel quantitative reverse-transcription PCR (qRT-PCR) for the enumeration of total bacteria, using meat micro-flora as a model. *Journal of Microbiological Methods* 77 (1):1–7. doi: 10.1016/j.mimet.2008.10.013.

Do Thi, N., and E. S. Hwang. 2014. Bioactive compound contents and antioxidant activity in Aronia (*Aronia melanocarpa*) leaves collected at different growth stages. *Preventive Nutrition and Food Science* 19 (3):204–12. doi: 10.3746/pnf.2014.19.3.204.

Durling, N. E., O. J. Catchpole, J. B. Grey, R. F. Webby, K. A. Mitchell, L. Y. Foo, and N. B. Perry. 2007. Extraction of phenolics and essential oil from dried sage (*Salvia officinalis*) using ethanol–water mixtures. *Food Chemistry* 101 (4):1417–24. doi: 10.1016/j.foodchem.2006.03.050.

Embuscado, M. E. 2015. Spices and herbs: Natural sources of antioxidants–A mini review. *Journal of Functional Foods* 18:811–9. doi: 10.1016/j.jff.2015.03.005.

Fernandes, R. P. P., M. A. Trindade, J. M. Lorenzo, P. E. S. Munekata, and M. P. De Melo. 2016. Effects of oregano extract on oxidative, microbiological and sensory stability of sheep burgers packed in modified atmosphere. *Food Control* 63:65–75. doi: 10.1016/j.foodcont.2015.11.027.

Friedman, M. 2007. Overview of antibacterial, antitoxin, antiviral, and antifungal activities of tea flavonoids and teas. *Molecular Nutrition & Food Research* 51 (1):116–34. doi: 10.1002/mnfr.200600173.

Ghasemzadeh, A., H. Z. Jaafar, and A. Rahmat. 2011. Effects of solvent type on phenolics and flavonoids content and antioxidant activities in two varieties of young ginger (*Zingiber officinale* Roscoe) extracts. *Journal of Medicinal Plants Research* 5 (7):1147–54.

Ghouila, Z., S. Laurent, S. Boutry, L. Vander Elst, F. Nateche, R. N. Muller, and A. Baaliouamer. 2017. Antioxidant, antibacterial and cell toxicity effects of polyphenols *Fromahmeur bouamer* grape seed extracts. *Journal of Fundamental and Applied Sciences* 9 (1):392–420. doi: 10.4314/jfas.v9i1.24.

Gorzynik-Debicka, M., P. Przychodzen, F. Cappello, A. Kuban-Jankowska, A. Marino Gammazza, N. Knap, M. Wozniak, and M. Gorska-Ponikowska. 2018. Potential health benefits of olive oil and plant polyphenols. *International Journal of Molecular Sciences* 19 (3): 686–13. doi: 10.3390/ijms19030686.

Govari, M., and A. Pexara. 2015. Nitrates and nitrites in meat products. *Journal of the Hellenic Veterinary Medical Society* 66 (3):127–40. doi: 10.12681/jhvms.15856.

Gradišar, H., P. Pristovšek, A. Plaper, and R. Jerala. 2007. Green tea catechins inhibit bacterial DNA gyrase by interaction with its ATP binding site. *Journal of Medicinal Chemistry* 50 (2):264–71. doi: 10.1021/jm060817o.

Gyawali, R., and S. A. Ibrahim. 2014. Natural products as antimicrobial agents. *Food Control* 46:412–29. doi: 10.1016/j.foodcont.2014.05.047.

Hashimoto, T., S. Kumazawa, F. Nanjo, Y. Hara, and T. Nakayama. 1999. Interaction of tea catechins with lipid bilayers investigated with liposome systems. *Bioscience, Biotechnology, and B2-Iochemistry* 63 (12):2252–5. doi: 10.1271/bbb.63.2252.

Hassan, O., and L. S. Fan. 2005. The anti-oxidation potential of polyphenol extract from cocoa leaves on mechanically deboned chicken meat (MDCM). *Lwt - Food Science and Technology* 38 (4):315–21. doi: 10.1016/j.lwt.2004.06.013.

Jia, N., B. Kong, Q. Liu, X. Diao, and X. Xia. 2012. Antioxidant activity of black currant (*Ribes nigrum* L.) extract and its inhibitory effect on lipid and protein oxidation of pork patties during chilled storage. *Meat Science* 91 (4):533–9. doi: 10.1016/j.meatsci.2012.03.010.

Kajiya, K., H. Hojo, M. Suzuki, F. Nanjo, S. Kumazawa, and T. Nakayama. 2004. Relationship between antibacterial activity of (+)-catechin derivatives and their interaction with a model membrane. *Journal of Agricultural and Food Chemistry* 52 (6):1514–9. doi: 10.1021/jf0350111.

Kamihira, M., H. Nakazawa, A. Kira, Y. Mizutani, M. Nakamura, and T. Nakayama. 2008. Interaction of tea catechins with lipid bilayers investigated by a quartz-crystal microbalance analysis. *Bioscience, Biotechnology, and Biochemistry* 72 (5):1372–5. doi: 10.1271/bbb.70786.

Karre, L., K. Lopez, and K. J. Getty. 2013. Natural antioxidants in meat and poultry products. *Meat Science* 94 (2):220–7. doi: 10.1016/j.meatsci.2013.01.007.

Katalinic, V., S. S. Mozina, I. Generalic, D. Skroza, I. Ljubenkov, and A. Klancnik. 2013. Phenolic profile, antioxidant capacity, and antimicrobial activity of leaf extracts from six *Vitis vinifera* L. varieties.

*International Journal of Food Properties* 16 (1):45–60. doi: 10.1080/10942912.2010.526274.

Katalinić, V., S. S. Možina, D. Skroza, I. Generalić, H. Abramovič, M. Miloš, I. Ljubenkov, S. Piskernik, I. Pezo, P. Terpinc, et al. 2010. Polyphenolic profile, antioxidant properties and antimicrobial activity of grape skin extracts of 14 *Vitis vinifera* varieties grown in Dalmatia (Croatia). *Food Chemistry* 119 (2):715–23. doi: 10.1016/j.foodchem.2009.07.019.

Kähkönen, M. P., A. I. Hopia, and M. Heinonen. 2001. Berry phenolics and their antioxidant activity. *Journal of Agricultural and Food Chemistry* 49 (8):4076–82. doi: 10.1021/jf010152t.

Kim, Y., K. L. Goodner, J. D. Park, J. Choi, and S. T. Talcott. 2011. Changes in antioxidant phytochemicals and volatile composition of *Camellia sinensis* by oxidation during tea fermentation. *Food Chemistry* 129 (4):1331–42. doi: 10.1016/j.foodchem.2011.05.012.

Konaté, K., A. Hilou, J. Mavoungou, A. Lepengué, A. Souza, N. Barro, J. Y. Datté, B. M'Batchi, and O. Nacoulma. 2012. Antimicrobial activity of polyphenol-rich fractions from *Sida alba* L.*(Malvaceae)* against co-trimoxazol-resistant bacteria strains. *Annals of Clinical Microbiology and Antimicrobials* 11 (1):5–6. doi: 10.1186/1476-0711-11-5.

Kozlowska, M., A. E. Laudy, J. Przybyl, M. Ziarno, and E. Majewska. 2015. Chemical composition and antibacterial activity of some medicinal plants from *Lamiaceae* family. *Acta Polonica Pharmaceutica* 72 (4):757–67.

Lapornik, B., M. P. Rošek, and A. G. Wondra. 2005. Comparison of extracts prepared from plant by-products using different solvents and extraction time. *Journal of Food Engineering* 71 (2):214–22. doi: 10.1016/j.jfoodeng.2004.10.036.

Lavola, A., R. Karjalainen, and R. Julkunen-Tiitto. 2012. Bioactive polyphenols in leaves, stems, and berries of Saskatoon (*Amelanchier alnifolia* Nutt.) cultivars. *Journal of Agricultural and Food Chemistry* 60 (4):1020–7. doi: 10.1021/jf204056s.

Lee, J. E., G. S. Kim, S. Park, Y. H. Kim, M. B. Kim, W. S. Lee, S. W. Jeong, S. J. Lee, J. S. Jin, and S. C. Shin. 2014. Determination of chokeberry (*Aronia melanocarpa*) polyphenol components using liquid chromatography–tandem mass spectrometry: Overall contribution to antioxidant activity. *Food Chemistry* 146:1–5. doi: 10.1016/j.foodchem.2013.09.029.

Liu, Y., L. C. McKeever, and N. S. Malik. 2017. Assessment of the antimicrobial activity of olive leaf extract against foodborne bacterial pathogens. *Frontiers in Microbiology* 8:1–8. doi: 10.3389/fmicb.2017.00113.

Lorenzo, J. M., J. Sineiro, I. R. Amado, and D. Franco. 2014. Influence of natural extracts on the shelf life of modified atmosphere-packaged pork patties. *Meat Science* 96 (1):526–34. doi: 10.1016/j.meatsci.2013.08.007.

Lou, Z., H. Wang, S. Zhu, C. Ma, and Z. Wang. 2011. Antibacterial activity and mechanism of action of chlorogenic acid. *Journal of Food Science* 76 (6):M398–M403. doi: 10.1111/j.1750-3841.2011.02213.x.

Ma, H., S. L. Johnson, W. Liu, N. A. DaSilva, S. Meschwitz, J. A. Dain, and N. P. Seeram. 2018. Evaluation of polyphenol anthocyanin-enriched extracts of blackberry, black raspberry, blueberry, cranberry, red raspberry, and strawberry for free radical scavenging, reactive carbonyl species trapping, anti-glycation, anti-$\beta$-amyloid aggregation, and microglial neuroprotective effects. *International Journal of Molecular Sciences* 19 (2):461. doi: 10.3390/ijms19020461.

Mennen, L. I., R. Walker, C. Bennetau-Pelissero, and A. Scalbert. 2005. Risks and safety of polyphenol consumption. *The American Journal of Clinical Nutrition* 81 (1):326S–9S. doi: 10.1016/j.fct.2014.06.009.

Mocan, A., G. Crișan, L. Vlase, O. Crișan, D. C. Vodnar, O. Raita, A.-M. Gheldiu, A. Toiu, R. Oprean, and I. Tilea. 2014. Comparative studies on polyphenolic composition, antioxidant and antimicrobial activities of *Schisandra chinensis* leaves and fruits. *Molecules* 19 (9):15162–79. doi: 10.3390/molecules190915162.

Nair, B. 2001. Final report on the safety assessment of benzyl alcohol, benzoic acid, and sodium benzoate. *International Journal of Toxicology* 20:23–50.

Nohynek, L. J., H. L. Alakomi, M. P. Kähkönen, M. Heinonen, I. M. Helander, K. M. Oksman-Caldentey, and R. H. Puupponen-Pimiä. 2006. Berry phenolics: Antimicrobial properties and mechanisms of action against severe human pathogens. *Nutrition and Cancer* 54 (1):18–32. doi: 10.1207/s15327914nc5401_4.

Nour, V., I. Trandafir, and S. Cosmulescu. 2014. Antioxidant capacity, phenolic compounds and minerals content of blackcurrant (*Ribes nigrum* L.) leaves as influenced by harvesting date and extraction method. *Industrial Crops and Products* 53:133–9. doi: 10.1016/j.indcrop.2013.12.022.

Nowak, A., A. Czyzowska, M. Efenberger, and L. Krala. 2016. Polyphenolic extracts of cherry (*Prunus cerasus* L.) and blackcurrant (*Ribes nigrum* L.) leaves as natural preservatives in meat products. *Food Microbiology* 59:142–9. doi: 10.1016/j.fm.2016.06.004.

Oh, J., H. Jo, A. R. Cho, S. J. Kim, and J. Han. 2013. Antioxidant and antimicrobial activities of various leafy herbal teas. *Food Control* 31 (2):403–9. doi: 10.1016/j.foodcont.2012.10.021.

Oliveira, B. D. A., Rodrigues, A. C. A. M. C. Bertoldi, J. G. Taylor, and U. M. Pinto. 2017. Microbial control and quorum sensing inhibition by phenolic compounds of acerola *(Malpighia emarginata)*. *International Food Research Journal* 24 (5):2228–37.

Oliveira, D. A., A. A. Salvador, A. Smânia, E. F. Smânia, M. Maraschin, and S. R. Ferreira. 2013. Antimicrobial activity and composition profile of grape (*Vitis vinifera*) pomace extracts obtained by supercritical fluids. *Journal of Biotechnology* 164 (3):423–32. doi: 10.1016/j.jbiotec.2012.09.014.

Pandey, K. B., and S. I. Rizvi. 2009. Plant polyphenols as dietary antioxidants in human health and disease. *Oxidative Medicine and Cellular Longevity* 2 (5):270–8. doi: 10.4161/oxim.2.5.9498.

Papuc, C., G. V. Goran, C. N. Predescu, V. Nicorescu, and G. Stefan. 2017. Plant polyphenols as antioxidant and antibacterial agents for shelf-life extension of meat and meat products: Classification, structures, sources, and action mechanisms. *Comprehensive Reviews in Food Science and Food Safety* 16 (6):1243–68. doi: 10.1111/1541-4337.12298.

Pellegrini, M. C., and A. G. Ponce. 2019. Beet (*Beta vulgaris*) and leek (*Allium porrum*) leaves as a source of bioactive compounds with anti-quorum sensing and anti-biofilm activity. *Waste and Biomass Valorization*:1–9. doi: 10.1007/s12649-019-00775-x.

Pennacchia, C., D. Ercolini, and F. Villani. 2011. Spoilage-related microbiota associated with chilled beef stored in air or vacuum pack. *Food Microbiology* 28 (1):84–93. doi: 10.1016/j.fm.2010.08.010.

Pereira, A. P., I. C. Ferreira, F. Marcelino, P. Valentão, P. B. Andrade, R. Seabra, L. Estevinho, A. Bento, and J. A. Pereira. 2007. Phenolic compounds and antimicrobial activity of olive (*Olea europaea* L. Cv. Cobrançosa) leaves. *Molecules* 12 (5):1153–62. doi: 10.3390/12051153.

Pereira, J. A., I. Oliveira, A. Sousa, P. Valentão, P. B. Andrade, I. C. Ferreira, F. Ferreres, A. Bento, R. Seabra, and L. Estevinho. 2007. Walnut (*Juglans regia* L.) leaves: Phenolic compounds, antibacterial activity and antioxidant potential of different cultivars. *Food and Chemical Toxicology* 45 (11):2287–95. doi: 10.1016/j.fct.2007.06.004.

Plaper, A., M. Golob, I. Hafner, M. Oblak, T. Šolmajer, and R. Jerala. 2003. Characterization of quercetin binding site on DNA gyrase. *Biochemical and Biophysical Research Communications* 306 (2):530–6. doi: 10.1016/S0006-291X(03)01006-4.

Plumed-Ferrer, C., K. Väkeväinen, H. Komulainen, M. Rautiainen, A. Smeds, J. E. Raitanen, P. Eklund, S. Willför, H.-L. Alakomi, M. Saarela, et al. 2013. The antimicrobial effects of wood-associated polyphenols on food pathogens and spoilage organisms. *International Journal of Food Microbiology* 164 (1):99–107. doi: 10.1016/j.ijfoodmicro.2013.04.001.

Plyuta, V., J. Zaitseva, E. Lobakova, N. Zagoskina, A. Kuznetsov, and I. Khmel. 2013. Effect of plant phenolic compounds on biofilm formation by *Pseudomonas aeruginosa*. *Apmis Journal Apmis* 121 (11):1073–81. doi: 10.1111/apm.12083.

Polat Yemis, G., S. Bach, and P. Delaquis. 2019. Antibacterial activity of polyphenol-rich pomegranate peel extract against *Cronobacter sakazakii*. *International Journal of Food Properties* 22 (1):985–93. doi: 10.1080/10942912.2019.1622564.

Puupponen-Pimiä, R., Nohynek, L. C. Meier, M. Kähkönen, M. Heinonen, A. Hopia, and K. M. Oksman-Caldentey. 2001.

Antimicrobial properties of phenolic compounds from berries. *Journal of Applied Microbiology* 90 (4):494–507. doi: 10.1046/j.1365-2672.2001.01271.x.

Radha Krishnan, K., S. Babuskin, P. A. S. Babu, M. Sasikala, K. Sabina, G. Archana, M. Sivarajan, and M. Sukumar. 2014. Antimicrobial and antioxidant effects of spice extracts on the shelf life extension of raw chicken meat. *International Journal of Food Microbiology* 171: 32–40. doi: 10.1016/j.ijfoodmicro.2013.11.011.

Radovanović, B. C., S. M. Anđelković, A. B. Radovanović, and M. Z. Anđelković. 2013. Antioxidant and antimicrobial activity of polyphenol extracts from wild berry fruits grown in southeast Serbia. *Tropical Journal of Pharmaceutical Research* 12 (5):813–9. doi: 10.4314/tjpr.v12i5.23.

Rosas-Burgos, E. C., A. Burgos-Hernández, L. Noguera-Artiaga, M. Kačániová, F. Hernández-García, J. L. Cárdenas-López, and Á. A. Carbonell-Barrachina. 2017. Antimicrobial activity of pomegranate peel extracts as affected by cultivar. *Journal of the Science of Food and Agriculture* 97 (3):802–10. doi: 10.1002/jsfa.7799.

Sagdic, O., I. Ozturk, M. T. Yilmaz, and H. Yetim. 2011. Effect of grape pomace extracts obtained from different grape varieties on microbial quality of beef patty. *Journal of Food Science* 76 (7):M515–M521. doi: 10.1111/j.1750-3841.2011.02323.x.

Serra, A. T., A. A. Matias, A. V. Nunes, M. C. Leitão, D. Brito, R. Bronze, S. Silva, A. Pires, M. T. Crespo, M. V. San Romão, et al. 2008. *In vitro* evaluation of olive-and grape-based natural extracts as potential preservatives for food. *Innovative Food Science & Emerging Technologies* 9 (3):311–9. doi: 10.1016/j.ifset.2007.07.011.

Shan, B., Y. Z. Cai, J. D. Brooks, and H. Corke. 2007. The *in vitro* antibacterial activity of dietary spice and medicinal herb extracts. *International Journal of Food Microbiology* 117 (1):112–9. doi: 10.1016/j.ijfoodmicro.2007.03.003.

Shan, B., Y. Z. Cai, J. D. Brooks, and H. Corke. 2009. Antibacterial and antioxidant effects of five spice and herb extracts as natural preservatives of raw pork. *Journal of the Science of Food and Agriculture* 89 (11):1879–85. doi: 10.1002/jsfa.3667.

Silva, M. M., and F. Lidon. 2016. Food preservatives–An overview on applications and side effects. *Emirates Journal of Food and Agriculture* 28 (6):366–73. doi: 10.9755/ejfa.2016-04-351.

Skupień, K., D. Kostrzewa-Nowak, J. Oszmiański, and J. Tarasiuk. 2008. *In vitro* antileukaemic activity of extracts from chokeberry (*Aronia melanocarpa* [Michx] Elliott) and mulberry (*Morus alba* L.) leaves against sensitive and multidrug resistant HL60 cells. *Phytotherapy Research* 22 (5):689–94. doi: 10.1002/ptr.2411.

Smeds, A. I., P. C. Eklund, and S. M. Willför. 2012. Content, composition, and stereochemical characterisation of lignans in berries and seeds. *Food Chemistry* 134 (4):1991–8. doi: 10.1016/j.foodchem.2012.03.133.

Sreelatha, S., and P. R. Padma. 2009. Antioxidant activity and total phenolic content of Moringa oleifera leaves in two stages of maturity. *Plant Foods for Human Nutrition* 64 (4):303–11. doi: 10.1007/s11130-009-0141-0.

Stojković, D. S., J. Živković, M. Soković, J. Glamočlija, I. C. Ferreira, T. Janković, and Z. Maksimović. 2013. Antibacterial activity of *Veronica montana* L. extract and of protocatechuic acid incorporated in a food system. *Food and Chemical Toxicology* 55:209–13. doi: 10.1016/j.fct.2013.01.005.

Stoops, J., S. Ruyters, P. Busschaert, R. Spaepen, C. Verreth, J. Claes, B. Lievens, and L. Van Campenhout. 2015. Bacterial community dynamics during cold storage of minced meat packaged under modified atmosphere and supplemented with different preservatives. *Food Microbiology* 48:192–9. doi: 10.1016/j.fm.2014.12.012.

Tabart, J., C. Kevers, J. Pincemail, J. O. Defraigne, and J. Dommes. 2006. Antioxidant capacity of black currant varies with organ, season, and cultivar. *Journal of Agricultural and Food Chemistry* 54 (17):6271–6. doi: 10.1021/jf061112y.

Tang, Q. L., A. R. Kang, and C. X. Lu. 2016. Phytochemical analysis, antibacterial activity and mode of action of the methanolic extract of *Scutellaria barbata* against various clinically important bacterial pathogens. *International Journal of Pharmacology* 12 (2):116–25. doi: 10.3923/ijp.2016.116.125.

Taylor, P. W., J. M. Hamilton-Miller, and P. D. Stapleton. 2005. Antimicrobial properties of green tea catechins. *Food Science and Technology Bulletin: Functional Foods* 2:71–81. doi: 10.1616/1476-2137.14184.

Teleszko, M., and A. Wojdyło. 2015. Comparison of phenolic compounds and antioxidant potential between selected edible fruits and their leaves. *Journal of Functional Foods* 14:736–46. doi: 10.1016/j.jff.2015.02.041.

Tiwari, B. K., V. P. Valdramidis, C. P. O' Donnell, K. Muthukumarappan, P. Bourke, and P. J. Cullen. 2009. Application of natural antimicrobials for food preservation. *Journal of Agricultural and Food Chemistry* 57 (14):5987–6000. doi: 10.1021/jf900668n.

Ulrey, R. K., S. M. Barksdale, W. Zhou, and M. L. van Hoek. 2014. Cranberry proanthocyanidins have anti-biofilm properties against *Pseudomonas aeruginosa*. *BMC Complementary and Alternative Medicine* 14 (1):1–12. doi: 10.1186/1472-6882-14-499.

Vagiri, M., A. Ekholm, S. C. Andersson, E. Johansson, and K. Rumpunen. 2012. An optimized method for analysis of phenolic compounds in buds, leaves, and fruits of black currant (*Ribes nigrum* L.). *Journal of Agricultural and Food Chemistry* 60 (42): 10501–10. doi: 10.1021/jf303398z.

Vallverdú-Queralt, A., J. Regueiro, M. Martínez-Huélamo, J. F. R. Alvarenga, L. N. Leal, and R. M. Lamuela-Raventos. 2014. A comprehensive study on the phenolic profile of widely used culinary herbs and spices: Rosemary, thyme, oregano, cinnamon, cumin and bay. *Food Chemistry* 154:299–307. doi: 10.1016/j.foodchem.2013.12.106.

Vrhovsek, U., A. Rigo, D. Tonon, and F. Mattivi. 2004. Quantitation of polyphenols in different apple varieties. *Journal of Agricultural and Food Chemistry* 52 (21):6532–8. doi: 10.1021/jf049317z.

Wang, Y., F. Li, H. Zhuang, X. Chen, L. Li, W. Qiao, and J. Zhang. 2015. Effects of plant polyphenols and α-tocopherol on lipid oxidation, residual nitrites, biogenic amines, and N-nitrosamines formation during ripening and storage of dry-cured bacon. *LWT - Food Science and Technology* 60 (1):199–206. doi: 10.1016/j.lwt.2014.09.022.

Wojdyło, A., J. Oszmiański, and P. Bielicki. 2013. Polyphenolic composition, antioxidant activity, and polyphenol oxidase (PPO) activity of quince (*Cydonia oblonga* Miller) varieties. *Journal of Agricultural and Food Chemistry* 61 (11):2762–72. doi: 10.1021/jf304969b.

Wu, T., M. He, X. Zang, Y. Zhou, T. Qiu, S. Pan, and X. Xu. 2013. A structure–activity relationship study of flavonoids as inhibitors of *E. coli* by membrane interaction effect. *Biochimica et Biophysica Acta (Bba) - Biomembranes* 1828 (11):2751–6. doi: 10.1016/j.bbamem.2013.07.029.

Wu, T., X. Zang, M. He, S. Pan, and X. Xu. 2013. Structure–activity relationship of flavonoids on their anti-*Escherichia coli* activity and inhibition of DNA gyrase. *Journal of Agricultural and Food Chemistry* 61 (34):8185–90. doi: 10.1021/jf402222v.

Xiong, L. G., Y. J. Chen, J. W. Tong, J. A. Huang, J. Li, Y. S. Gong, and Z. H. Liu. 2017. Tea polyphenol epigallocatechin gallate inhibits *Escherichia coli* by increasing endogenous oxidative stress. *Food Chemistry* 217:196–204. doi: 10.1016/j.foodchem.2016.08.098.

Yi, S., W. Wang, F. Bai, J. Zhu, J. Li, X. Li, Y. Xu, T. Sun, and Y. He. 2014. Antimicrobial effect and membrane-active mechanism of tea polyphenols against *Serratia marcescens*. *World Journal of Microbiology and Biotechnology* 30 (2):451–60. doi: 10.1007/s11274-013-1464-4.

Yi, S. M., J. L. Zhu, L. L. Fu, and J. R. Li. 2010. Tea polyphenols inhibit *Pseudomonas aeruginosa* through damage to the cell membrane. *International Journal of Food Microbiology* 144 (1):111–7. doi: 10.1016/j.ijfoodmicro.2010.09.005.

Yuan, W., and H. G. Yuk. 2018. Antimicrobial efficacy of *Syzygium antisepticum* plant extract against *Staphylococcus aureus* and methicillin-resistant *S. aureus* and its application potential with cooked chicken. *Food Microbiology* 72:176–84. doi: 10.1016/j.fm.2017.12.002.

Zhang, J., X. Rui, L. Wang, Y. Guan, X. Sun, and M. Dong. 2014. Polyphenolic extract from *Rosa rugosa* tea inhibits bacterial quorum sensing and biofilm formation. *Food Control* 42:125–31. doi: 10.1016/j.foodcont.2014.02.001.

Zhang, L., S. G. Xu, W. Liang, J. Mei, Y. Y. Di, H. H. Lan, Y. Yang, W. W. Wang, Y. Y. Luo, and H. Z. Wang. 2015. Antibacterial activity and mode of action of *Mentha arvensis* ethanol extract against multidrug-resistant *Acinetobacter baumannii*. *Tropical Journal of Pharmaceutical Research* 14 (11):2099–106. doi: 10.4314/tjpr.v14i11.21.

Zhang, Q. Q., Jiang, M. X. Rui, W. Li, X. H. Chen, M. S. and Dong, M. S. 2017. Effect of rose polyphenols on oxidation, biogenic amines and microbial diversity in naturally dry fermented sausages. *Food Control* 78:324–30. doi: 10.1016/j.foodcont.2017.02.054.

Zhang, Y. M., and Rock. C. O. 2004. Evaluation of epigallocatechin gallate and related plant polyphenols as inhibitors of the FabG and FabI reductases of bacterial type II fatty-acid synthase. *Journal of Biological Chemistry* 279 (30):30994–1001. doi: 10.1074/jbc.M403697200.

Zhu, H. L., G. Chen, S. N. Chen, Q. R. Wang, L. Wan, and S. P. Jian. 2019. Characterization of polyphenolic constituents from *Sanguisorba officinalis* L. and its antibacterial activity. *European Food Research and Technology* 245 (7):1487–98. doi: 10.1007/s00217-019-03276-2.