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Antibacterial Activity of Plant Polyphenols

Galina Satchanska

Abstract

This chapter focuses on methods of polyphenol isolation and on the antibacterial activity of different polyphenols found in herbs, spices, fruits and vegetables. Polyphenols are secondary metabolites which protect plants from different pathogens, such as viruses, bacteria, fungi, insects, and herbivores. Currently, about 9000 polyphenols found in more than 480 plants are known. Their amount fluctuates across different species and varieties. This chapter describes conventional and novel methods for extraction, the influence of the type of solvents, solvent concentration and temperature on the yield. The highest yield is obtained at 70% of methanol and ethanol, and at 90% of acetone. Extraction at 80°C leads to higher amounts of polyphenols than extraction at 100°C. Polyphenols are usually metabolized in the human liver but can also remain unaffected as they pass through the gastrointestinal tract. The main location for their uptake is the colon. They exhibit a wide range of antibacterial activity against *Pseudomonas aeruginosa*, *Staphylococcus aureus*, *Streptococcus epidermidis*, *Klebsiella pneumoniae*, *E. coli*, *Listeria monocytogenes*, *Acinetobacter* sp., *Proteus* sp., *Micrococcus* sp., and *Bacillus* sp. All these plants, rich in antimicrobial polyphenols, represent a promising and powerful source of highly effective novel antibacterial substances in the current era of ubiquitous antibiotic resistance.

Keywords: plant polyphenols, isolation, antibacterial activity

1. Introduction

The widespread antibiotic resistance in the last 20 years has become one of the biggest worldwide threats to mankind. Plants are valuable reservoir of novel antimicrobials and their secondary metabolites as polyphenols demonstrate strong antimicrobial activity at extremely low concentrations. Precursor of polyphenols is phenol which consist of one aromatic ring and a hydroxyl group. Polyphenols as more complex substances are polyaromatic and contain a few hydroxyl groups. They are divided into four main groups: Flavonoids, Lignans, Phenolic acids, and Stilbenes. Among them, flavonoids are the most numerous. All polyphenols play an important role in the defense of plants against bacteria, viruses, fungi, insects and herbivores. Polyphenol synthesis derives from two aromatic amino acids – tyrosine and phenylalanine. As secondary plant metabolites, their amount is estimated at only around 10% of plant metabolites [1].

Among the 300,000 plant species that exist in the world only 15% have been investigated for their pharmacological potential, the rest of them are a potential source

of novel natural antimicrobial products [2]. According to the WHO, the global market of plant products is estimated at the huge amount of US \$83 billion and currently continues to grow. Usually, the daily polyphenol human intake varies between 20 and 500 mg, taken *via* onions, tomatoes, red wine and many other foods and beverages [3]. Once inside the body, phenol is retained there bound to other molecules, most often to proteins. Absorbed or unabsorbed, while passing through the gastrointestinal tract polyphenols strongly influence human microbiota. They inhibit gastrointestinal pathogenic bacteria and enrich the beneficial intestinal bacteria. In this way, they significantly improve human health [4].

Currently, more than 9000 polyphenols have been identified. Some major representatives of polyphenols are shown in **Figure 1**.

Salicylic acid (2), an ortho-hydroxylated benzoic acid, is a beta hydroxy acid that occurs as a natural compound in plants. More than 2000 years ago, Hippocrates (c. 300 BC) cured rheumatism and inflammation with white willow (*Salix alba*) leaves and bark extracts, both containing the precursor of salicylic acid – salicin. Cardamom seeds, a typical aroma additive to tea and Arabian coffee in Asia and the Middle East, also contains salicin. It is highly active as an anti-inflammatory agent and a proven antibacterial agent. Salicylic acid is detectable in most of human organs and tissues being most abundant in saliva. It persists in all eukaryotic organisms. Foods processed from cereals are rich salicylic acid easily recognizable by its phenol-like smelling.

Gallic acid (3), also named gallate falls in the class Gallic acids [5]. It comprises of 3, 4, 5-trihydroxybenzoic acid. Gallic acid can be found in various foods, such as apple, ginger, yellow pepper, hazelnuts, and oak bark. Gallic acid is recognized as strong antioxidant.

Figure 1.

Structure and molecular formula of main polyphenols: (1) phenol (C_6H_5OH); (2) 2-Hydroxybenzoic acid (salicylic acid) (HOC_6H_4COOH); (3) 3,4,5-Trihydroxybenzoic acid (Gallic acid) ($C_6H_2(OH)_3COOH$); (4) 4-Hydroxycinnamic (p-Coumaric acid) ($C_9H_8O_3$); (5) 3,4-Dihydroxycinnamic acid (Caffeic acid) ($C_9H_8O_4$); (6) 4-Hydroxy-3-methoxycinnamic acid (Ferulic acid) ($C_{10}H_{10}O_4$); (7) 4-hydroxy-3-(3-oxo-1-phenylbutyl)chromen-2-one, Warfarine (Coumarins) ($C_{19}H_{16}O_4$); (8) 1,4-benzoquinone (p-benzoquinone) (Quinone) ($C_6H_4O_2$); (9) 2,3-Dihydroflavone (flavone) ($C_{15}H_{12}O_2$); (10) 2-phenyl-4H-chromen-4-one (flavone) ($C_{15}H_{10}O_2$); (11) 3-Hydroxy-2-phenyl-4H-chromen-4-one (Flavonol) ($C_{15}H_{10}O_3$); (12) 7-(1,3-benzodioxol-5-yl)-6-hydroxy-5-methoxy-2,2-dimethylpyrano[3,2-g]chromen-8-one (Robustin) (Isoflavonoid) ($C_{22}H_{18}O_7$); (13) 2-(4-Hydroxyphenyl)chromenylium-3,5,7-triol (Pelargonidine) (Anthocyanidine) ($C_{15}H_{11}O_5^+$); (14) Anthocianins; (15) 1,3,6-tri-O-galloyl-beta-D-glucose (Gallotannin) ($C_{27}H_{24}O_{18}$); and (16) Elagitannin ($C_{44}H_{32}O_{27}$) (source of figures and short description of substances below [5]).

Hydroxycinnamic acids (4), known also as coumaric acid, contains cinnamic acid, where the benzene ring is hydroxylated at C-4. Inside the cell, hydroxycinnamic acids are located in the cytoplasm and mitochondria. Similarly to salicylic acid, *trans*-4-coumaric acid is present in all eukaryotes. Plants like green pepper, apricot, and blueberry are excellent source of this acid. Like gallic acid, hydroxycinnamic acids can be detected in human feces, urine, and blood.

Caffeic acid (5) is a hydroxycinnamic acid derivative. It exhibits antioxidant, anti-inflammatory, and antineoplastic activities and protect DNA from free radicals damage. Bountiful in skin and prostate gland, caffeic acid shows suppressive effect on prostate cancer proliferation. Along with its beneficial effect, the substance is classified as a possible carcinogen (IARC – International Agency for Research on Cancer (WHO) classification of cancerogenic xenobiotics – Group 2B) and toxic compound [5]. Many plants are rich in caffeic acid: apricot, prunes, salvia, spearmint, thyme, aronia, sunflower seeds, barley and rye. Oddly, coffee contains modest concentrations of caffeic acid in contrast to argan oil.

Ferulic acid (6), a tyrosin-similar compound comprises of the water soluble *trans*-cinnamic acid. Main location of the substance is the plant cell is the cell wall. Its name originates from the giant fennel (*Ferula communis*). Rich in ferulic acid are root vegetables and sweet popcorn. Being a constituent of the plant biopolymer lignocellulose the ferulic acid is involved in accumulation of this most abundant biowaste on Earth. Pronounced apoptosis inhibitor and cardioprotector, ferulate also helps the skin aging retardation inhibiting melanin formation. Used widely as food preservative [5] it can be successfully excreted *via* human epidermis.

Warfarin (7) falls in the class of 4-hydroxycoumarins and is one of the best synthetic oral anticoagulants. It constrains the synthesis of blood clotting factors which depends on Vitamin K. The key role of Vitamin K is the synthesis of one unusual for proteins amino acid – *gamma*-carboxyglutamic acid, an important for the biological activity of clotting proteins component. Warfarin is applied in the treatment of various types of embolism like cerebral or lung embolism. Vit. K exists in two forms: Vit. K1 (phylloquinone) which is synthesized by plants and can be found mainly in green leafy vegetables, and Vit. K2 (menaquinone) which is synthesized by the probiotic lactic acid bacteria in the human intestine and is also abundant in the fermented dairy products.

1,4-Benzoquinone (8) is a member of *p*-benzoquinones and a metabolite of benzene. 1,4-Benzoquinone possess two C=O groups attached at the 1- and 4-positions at of the aromatic ring. Inside the cell, mitochondria and the cytoplasm are the cell structures docking quinone which enforce specific enzymatic reactions. Quinone is capable to turn into orotic acid and when accumulated in the human blood orotic acid leads to aciduria resulting in quick liberation of ammonia. Often 1,4-Benzoquinone is transformed to glycerol 3-phosphate, a key substance of Glycolysis. Quinone is also responsible for the Vit. B₁₂ (cyanocobalamin) catabolism. Vit. B₁₂ is synthesized by probiotic bacteria in the human colon and its deficiency cause anemia. Anise is one of the richest sources of 1,4-Benzoquinone.

Flavone (9) is a lipid molecule and member of the class of flavanones. In the cell it is harbored in the cytoplasmic membrane and among the human tissues the most abundant is placenta. Amid fruits pomegranate is excessive in this substance while out of spices rosemary is the wealthiest one.

3-Hydroxyflavone (10) belongs to flavonols [5]. Similarly to flavanone, it is spotted in the cell membrane and is a water insoluble compound. 3-Hydroxyflavone is precursor of tautomycin known an anti-aging and anti-Parkinsonian medicine. Foods abundant in this polyphenol are brassicas and papaya.

Vegetables	Fruits	Grains	Beans	Herbs&Spices	Beverages
Artichoke	Apples	Oat	Black beans	Basilicum	Black tea
Asparagus	Apricots	Rye	Soy meat	Black tea	Coffee
Broccoli	Black chokeberry	Whole grains	Soy milk	Celery	Dark chocolate
Capers	Black currant	Wheat	Sprout	Cinnamon	Ginger
Carrots	Black elderberry		White beans	Cummin	Green tea
Cayenne pepper	Black grapes			Curry	Olive oil
Garlic	Blackberry			Ginger	Rapeseed oil
Olives	Blueberry			Green tea	Red wine
Potatoes	Cherry sour			Majoran	Vinegar
Red lettuce	Cherry sweet			Oregano	
Onion	Grapefruit			Parsley	
Spinach	Nectarines			Peppermint	
	Peaches			Rosemary	
	Pears			Sage	
	Pomegranate			Spearmint	
	Plum			Star anise	
	Raspberry				
	Strawberry				

Table 1.
Foods of daily diet supplying polyphenols (Adapted after Perez-Jumenez et al. [7] and Mustafa et al. [8]).

Another derivative of flavone is *Flavonol* (11). Due to its rich yellow color it was used for centuries in wool and silk dyeing. Flavonol is capable to bind essential and heavy metal ions.

Generally, flavonoids are main contributors to the flavor of fruits and the bitterness of citruses. Naringin, tangeritin, quercetin and neohesperidin impart the bitter taste in citruses, while the bitterness of wine is due to catechins and epicatechins [6].

Pelargonidin (13) can be found in almost all berries – blueberries, blackberries, cranberries, raspberries, strawberries, and aronia. Large amounts of pelargonidin are typically found also in plums and pomegranates, a polyphenol responsible for the color of radishes.

Gallotannins (15) is a class of tannins obtained by condensation of the carboxy group of gallic acid and the hydroxy group of glucose. Rich in gallotannins are pomegranates, strawberries and gallnuts. In **Table 1** are presented the foods supplying polyphenols.

2. Isolation of polyphenols

Isolation of polyphenols is a challenging procedure due to the instability and complex structure of these compounds. Most often polyphenols are harbored in plant leaves and gymnosperm, and within the cell in the cell wall and vacuoles associated

with the nuclei. The covalent bonding of polyphenols with the plant structures is a limiting factor for their liberation [9]. Additionally, other factors influence the recovery of phenolic compounds from plant samples: location in plant tissues, extraction method, sample size, storage conditions and possible subsequent chemical conversions. A wide spectrum of plant secondary metabolites, including polyphenols can be obtained using water or organic solvents.

2.1 Conventional extraction using solvents

These methods are widely used. Washed or dried plant material is finely ground and subjected to solvent extraction. The most commonly used solvents are water, hexane, ether, chloroform, acetone, benzene, ethanol and methanol. All these solvents are effective in taking out bioactive compounds i.e. polyphenols from the cell.

EtOH dissolves alkaloids, glycosides and dyes but does not dissolve gum, waxes or fats. It easily penetrates the cell membrane and fast and effortlessly extracts the cell metabolites. A disadvantage of ethanol is its volatility and flammability.

Acetone dissolves large amount of substances both hydrophilic and lipophilic. It is excellent for tannin extraction. Its advantage is not only the prevention of microorganism growth but also the easy evaporation and low cost extraction. Like ethanol, it is flammable and volatile.

Chloroform, *ether* and *bischloromethanol*. Chloroform is suitable for tannin extraction, ether for coumarins and tannins, and bischloromethanol – for terpenoids but not for phenolic compounds. All three solvents evaporate easily and are low-cost. Their disadvantages besides volatility and flammability are explosiveness and toxicity.

According to the paper of Alothman et al. [10], who studied pineapple, banana and guava, the percentage of different solvents strongly influence the polyphenol yield. Investigating polyphenol extraction with methanol, ethanol and acetone at concentration 90, 70, and 50%, authors found the highest yield at 70% of ethanol and methanol, and at 90% of acetone. Among the three fruits, guava showed to be the most abundant in polyphenols.

The main steps of polyphenol extraction are: (1) Sample grinding, (2) Extraction, (3) Filtration, (4) Concentration, and (5) Drying.

The conventional methods of extraction are maceration, infusion, percolation, Soxhlet extraction, and water-alcoholic extraction *via* fermentation. The most preferable of these methods is the Soxhlet extraction. It operates as follows: the finely ground plant sample is placed into a filter bag, the solvent is heated using a heating device and its vapors condense in a condenser. The condensed solvent drips on the plant material (bag) and extracts the polyphenols from it. After the extraction, the solvent is discarded from the polyphenol extract using vacuum evaporation. The advantages of the Soxhlet method are the high amount of extract yielded with a small amount of solvent, the low cost and the ease of conducting the process.

2.2 Novel methods of extraction

Ultrasonic extraction. During the process, the plant cell wall is broken by waves with a frequency of 10 kHz to 10 MHz. The polyphenol yield is improved up to 35% [9]. The best yield can be obtained at a 4:1 solvent/solute ratio for 200 ms extraction time at 400 W ultrasonic power. The disadvantage of this method is the degradation of anthocyanins due to the formation of OH radicals by the sonolysis of water and the high amplitude of treatment.

Microwave extraction. The solvent and plant sample are treated with microwaves and thus the phenolic compounds are released in the solvent. The advantages of the method are the low cost, smaller volume of solvent, temperature control and higher antioxidant activity of the product [11]. As the power increases, the amount of phenolic acids increases. In contrast, the extended treatment at 250 W leads to a decrease in total flavonoids.

Pressurized liquid extraction. Using this method, the temperature increases from 50 to 200°C and the pressure from 3.5 to 200 MPa. The advantage of the method is the better penetration of the solvent in the plant sample due to the increased pressure at high temperature.

Pulse electric field extraction. This method is used for pre-treatment of the plant material resulting in enhanced amount of polyphenols. Even under low electric field, the permeability of the plant cell is increased. Anthocyanins yield from grape pulp with grape skin is improved up to 28% when using the following conditions: 50 pulses and 1 Hz at 10 kV [12].

The best way to determine polyphenols remains HPLC-DAD (high-performance liquid chromatography with diode array detection). Many phenolic compounds, such as epicatechin, vanillic acid, quercetin, kaempferol, epigallocatechin, rutin, and myricetin were analyzed using this method. Structure elucidation of polyphenols can be implemented using gas chromatography-mass spectrometry [13].

3. Antimicrobial activity of polyphenols from herbs and spices

Longevity of the community inhabiting Mediterranean area is due to their polyphenols rich diet. Most of Mediterranean herbs containing polyphenols were described to possess antibacterial activity against both Gram (+) and Gram (–) bacteria. Shehadi et al. [14] reported growth inhibition of *Bacillus subtilis* by *Rosemary officinalis*, *Eugenia caryophyllata*, *Mentha piperita*, and *Prunus avium*. According to the authors the major inhibition was observed by the extract of wild cherry (4 mg/ml) followed by cloves (1.6 mg/ml). As described, the phenolic extracts were recovered at 80°C. An important finding of the study was the extracts' strength depends on the temperature at which they were obtained. Extracts revealed at 100°C possess lower bactericidal activity (2.4 mg/ml – wild cherry and 0.6 mg/ml – cloves) compared to those eluted at 80°C.

Alamri and Moustafa [15] reported action against different bacteria of *Ricinus communis* L.) and *Allium ampeloprasum* var. *porrum*. Both extracts were able to inhibit the growth of Gram (+) pathogens *Staphylococcus aureus*, *Streptococcus epidermidis*, and of Gram (–) *Pseudomonas aeruginosa*, *E. coli*, *Klebsiella pneumoniae*, *Proteus* sp., and the pronounced agent of nosocomial infections – *Acinetobacter*. Authors discussed the abundant polyphenolic content of both extracts including at least six polyphenols and the higher activity of *R. communis* (27 mm) compared to *Allium ampeloprasum* (23 mm). Strongest inhibition was observed mainly against the pathogenic Gram (–) *P. aeruginosa*.

Data about the influence of different solvents for polyphenol extraction on the antibacterial activity were published by Harfouch et al. [16], Rizwana et al. [17]. Studying the effectiveness of methanolic and ethanolic extract of *Maritica aurea* L. the authors found that the methanolic one is more powerful against the Gram(+) chemolytic *Streptococcus pyogenes* (23 mm) and skin pathogen *S. aureus* (21 mm) compared to ethanolic extract. The inhibition is performed *via* bacterial cell wall damage.

Besides the herbs, various medicinal plants demonstrate high polyphenol concentrations [18]. *Hypericum perforatum* L., *Origanum vulgare* L., and *Melissa officinalis*

L. along with four other medicinal plants were investigated for phenolic presence. Recently, the antibacterial activity of methanolic extracts of both flowers and leaves was proved, including wild hypericum collected from Kashmir, Himalaya.

Bactericidal effect of *Geranium macrorrhizum* was described by Ivancheva et al. [19]. This plant is known with its high polyphenol concentrations consisting mainly of flavonoids and tannins and in this particular study water-alcoholic extracts of the plant were investigated. The tested extracts inhibited the growth of several pathogenic bacteria *S. aureus.*, *E. coli*, *K. pneumonia*, and *P. aeruginosa*.

Another plant used as medicinal plant, spice and herb – the sanogenous parsley also showed antibacterial properties. Several classes of polyphenols persist in parsley mostly flavonoids like kaempferol, apigenin and luteolin. Average content of flavonoids is approximately 100 mg/100 g fresh weight [20]. According to Tomov et al. [21] the green minced parsley leaves demonstrated weak antibacterial effect against *E. coli* and *B. subtilis* (see **Table 2**).

The antimicrobial activity of lavandula against *Staphylococcus epidermidis* was described in detail by Zou et al. [22]. The antimicrobial activity of the lavandula phenolic extract was reported by a Moroccan research team [23]. The authors described that Lavandula inhibits the growth of clinical *Listeria monocytogenes* and *S. aureus* isolates from a Moroccan hospital. Georgiev et al. [24] also reported on the antioxidant activity of *Lavandula vera*.

Mihajlova et al. [25] studied the phenolic profile and the antibacterial activity of mallow (*Malva silvestris*).

Green tea is also excessive in polyphenols and demonstratie robust antimicrobial action [26]. Green tea polyphenols consist mainly of flavonoids. Catechins are in the highest concentration of 30–40%. Four main catechins were isolated from tea: epicatechin (EC), epicatechin-3-gallate (ECG), epigallocatechin (EGC), and epigallocatechin-3-gallate (EGCG), as reported by Raygaert [27]. In green tea, EGCG is the most abundant, representing approximately 59% of the total catechins. It is important to note that during the initial steaming process of tea production the enzyme polyphenol oxidase is destroyed and thus the polyphenol content is protected. Catechins of green tea damage the bacterial cell membrane, inhibit the fatty acid synthesis of

No.	Vegetable/plant vegetative organ	Inhibition zone d on <i>B. subtilis</i> NIBMCC 8752	Inhibition zone d on <i>E. coli</i> NIBMCC 8751
1.	Parsley (leaves)	2	0
2.	Tomato (seeds)	5	0
3.	Cayenne pepper (tissue discs)	24	25
4.	Cayenne pepper (seeds)	7	11
5.	Onion brown skin (mature bulbs)	27	3
6.	Onion red skin (mature bulbs)	25	3
7.	Onion young (fresh bulbs)	0	0
8.	Garlic (mature bulbs)	7	30
9.	Garlic young (fresh bulbs)	2	0

Table 2.
Antibacterial activity of polyphenol containing vegetables (inhibition zones d in mm) against B. subtilis and E. coli type strains, personal results.

bacteria and DNA-gyrase during bacterial replication. In the same paper the inhibitory effect of green tea catechins on the binding of *Helicobacter pylori* to the Toll-like receptor-4 (TLR-4) on gastric epithelial cells was described.

4. Antimicrobial activity of polyphenols from fruits

Polyphenol abundant fruits also exhibit antibacterial action. In pomegranate juice (*Pommes granatum* L.) were obtained caffeic acid, gallic acid and epigallocatechin. Latest substance can be found as prior component also in the green tea. Divyarhree and Kunniath [28] studied its hydrochloric extract on the oral cavity inhabiting bacteria colonizing the dental plaque. Authors' research showed the extract inhibited *Porphyromonas gingivalis*, *Prevotella intermedia*, and *Aggregatibacter actinomycetem-comitans*, all responsible for assaultive periodontitis.

Noticeable Mediterranean fruits wealthy in polyphenols are olives (*Olea europea*). The general phenolic component responsible for their health beneficial effect is hydroxytyrosol [29]. Besides its antimicrobial activity, hydroxytyrosol is a superior antioxidant and radical scavenger, which induces apoptosis and arrests the cell cycle in cancer cells. Usually hydroxytyrosol is renally evacuated. Other phenolic compounds in olives are tyrosol, glycoside oleuropein, oleocanthal, and oleacein. Hydroxytyrosol and oleuropein demonstrated antimicrobial activity [30] against ATTC bacterial strains and clinical bacterial isolates.

In vitro antibacterial (MIC and MBC) effect of *Sida alba*, a polyphenol-containing and typical for India and Arabian peninsula plant was obtained by Konate et al. [31].

The antimicrobial activity of fruit extracts was reported by Marinova et al. [32], who examined more than 20 fruits for their polyphenolic content. The analysis included *Pyrus communis*, *Malus pumila*, *Prunus domestica*, *Prunus persica*, *P. avium*, *Prunus cerasus vulgaris*, *Rubus idaeus*, *Fragraria vesca*, *Vitis vinifera*, *Cornus mas*, *Rubus fruticosus*, *Viccinum mirtilus*, and *Ficus carica*. The authors found the highest polyphenol content in *Viccinum mirtilus* (European black berry) – 670 mg GAE/100 g fresh mass followed by *C. mas* (dogwood) – 429, and the lowest content was demonstrated by *P. persica* (peach) – 50 GAE/100 g.

Tannins, a common polyphenolic substances in all types of red wines were reported as natural antibacterial substances as well [33].

Polyphenols from tobacco leaves extracted with 80% ethanol manifest antibacterial activity against *Escherichia coli*, *S. aureus* and *B. subtilis* with inhibition zones ranging 13, 17 and to 20 mm [34].

Polyphenols play synergistic effect when applied in combinations with antibiotics [35, 36]. Their mode of action is straight inhibition of the pathogenic microorganisms' virulence factors.

5. Antimicrobial activity of polyphenols from vegetables

Some authors report antibacterial activity of tomato. Tomato ranks second in world consumption among all vegetables [37]. Our previous research [21] showed no significant difference in the effect of raw or cooked tomato products against bacteria. The antibacterial effect was not a strong one (up to 7 mm zone). Seeds of two out of six tomato varieties slightly inhibited the growth of *B. subtilis* and showed no antibacterial activity against

E. coli. With regular consumption of tomato this activity plays a preventive role against bacterial infections. The inhibition zones were 4–7 mm on agar plates. These results coincided with the results obtained by Unnisa et al. [38], who reported low antibacterial activity of tomato fruit against *E. coli*. The elucidation of the low antibacterial activity of tomatoes is related with the low polyphenol concentration in this vegetable. According to Marti et al. [37] the following amounts of polyphenols (mg/100 g fresh weight) were obtained from tomatoes: naringine chalcone (0.9–18.2), rutin (0.5–4.5), quercetin (0.7–4.4), chlorogenic acid (1.4–3.3), naringenin (0–1.3), kaempferol-3 rutinoside (0–0.8), *p*-coumaric acid (0.2–0.5), ferulic acid (0.2–0.5) and kaempferol (0–0.2).

Onions are vegetables with strong antimicrobial activity. The antibacterial activity of garlic (*Allium sativa*) was studied by Chen et al. [39], Tomov et al. [21] and Obied et al. [40]. As reported by Tomov et al. [21], *Allium sativa* possesses pronounced antibacterial activity against Gram (–) *E. coli* (30 mm), and lower activity towards Gram (+) *B. subtilis* (7 mm). However, *Allium cepa*, also rich in polyphenols, showed lower antibacterial activity in comparison to garlic [21] against the tested strains.

Ramos [41] described *A. cepa* extracts to be more effective against Gram (+) microorganisms, while Gram (–) bacteria were reported to be less susceptible. He discussed the water extracts from yellow onion skin and found that even onion skin is active against Gram (–) bacteria.

An interesting finding is that the synthesis of antibacterial substances in *Allium sativum* and *A. cepa* occurs intensively in mature onion and garlic, not in the green leafy ones. Moreover, the synthesis of the antibacterial compounds continues when they are stored at room temperature (22°C) but stops at refrigerator (5–8°C).

Anthocyanins and flavonols are two flavonoids found out in *A. cepa*. Anthocyanins give the red color of some varieties. Flavonols as quercetin are responsible for the orange-brown onion skin. More than 25 different flavonols are currently recovered from the onion. One of them – quercetin was ubiquitous in all onion varieties. About 80% of the total flavonols in *A. cepa* are represented by quercetin 4'-glucoside and quercetin 3,4'-glucoside.

Cayenne pepper is remarkable with its lofty phenol content [42]. The authors supplied data that the ripening and cooking processes lead to an increase in the polyphenol concentration in 16 out of 18 studied cultivars. Chili peppers lead the ranking of antimicrobial activity, as shown by Omolo et al. [43]. Our experiments [21] on cayenne pepper fruits and seeds showed growth inhibition of *E. coli* and *B. subtilis*. Smashed pepper tissues showed no antibacterial effect, while the pepper discs demonstrated pronounced antibacterial activity against both *E. coli* (25 mm) and *B. subtilis* (24 mm). The results of Mariângela et al. [44], Koffi-Nevri et al. [45], and Nascimento et al. [46] describe similar activity of the capsicum fruit against both Gram (+) and Gram (–) bacteria. An interesting finding was that similarly to tomatoes seeds, pepper seeds exhibited inhibition on the growth of *E. coli* (11 mm) and *B. subtilis* (7 mm). Data about the antibacterial activity of honey derived polyphenols is discussed by Cianciosi et al. [47], Uthurry et al. [48] and Sateriale et al. [49]. Useful information about the richest dietary sources of polyphenols are available at the Phenol Explorer Database, Rothwell et al. [50] and Perez-Jimenez et al. [7].

6. Conclusions

Selected herbs, spices, fruits and vegetables contain high polyphenol concentrations. They show pronounced antibacterial activity acting against a plethora of

pathogenic Gram(–) and Gram(+) bacteria as *P. aeruginosa*, *S. aureus*, *Streptococcus epidermidis*, *K. pneumoniae*, *E. coli*, *L. monocytogenes*, *Acinetobacter* sp., *Proteus* sp., *Micrococcus* sp., and *Bacillus* sp. Extraction of polyphenols is challenging and depends on the method, solvent, solvent percentage, temperature of isolation and plant sample. Plant polyphenolic extracts obtained at 80°C possess higher antibacterial activity compared to those extracted at 100°C. Numerous herbs, spices, fruits, and vegetables rich in polyphenols are valuable sources of novel highly effective antimicrobial substances.

Acknowledgements

This work was funded by The Central Fund for Strategic Development, New Bulgarian University, Sofia, Bulgaria - Grant № 1593/21.12 2021.

Conflict of interest

The author declares no conflict of interest.

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