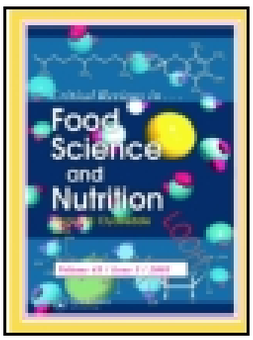

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REVIEW

Phenolic compounds in Nordic berry species and their application as potential natural food preservatives

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ABSTRACT

An increasing demand for natural food preservatives is raised by consumers. For Nordic berry species, abundance of phenolic compounds and potent activities of anti-oxidation and anti-bacteria enables a great potential as food preservatives. This review provides a systematic examination of current literature on phenolic profiles, anti-oxidative and anti-bacterial activities of various extracts of Nordic berry species, as well as the impact of various structure features of phenolics on the bioactivities. Special attention is placed on exploitation of leaves of berry species and pomaces after juice-pressing as side-streams of berry production and processing. The current progress and challenges in application of Nordic berry species as food preservatives are discussed. To fully explore the potential application of Nordic berry species in food industry and especially to valorize the side-streams of berry cultivation (leaves) and juice-pressing industry (pomaces), it is crucial to obtain extracts and fractions with targeted phenolic composition, which have high food preserving efficacy and minimal impact on sensory qualities of food products.

KEYWORDS

Anti-bacterial; anti-oxidative; berry; natural food preservative; phenolic extracts; side-streams

Introduction

Berries of different species have received a world-wise attention in last decades for being a rich source of phenolic compounds. A large number of *in vitro* and animal studies have confirmed that these compounds are responsible for various bioactivities and health-promoting benefits of berries, and thus berries are highly recommended for a daily diet to promote wellbeing (Nile and Park 2014; Yang and Kortesniemi 2015). Except consumed in fresh, berries are mainly used in beverage production or in processed foods as functional ingredients to provide special flavors. For food industry, it is of great interests and challenges to maximum utilize phenolic compounds present in different berry species. Currently, the main progress of utilization of berry-derived phenolics is that anthocyanins have been allowed by the European Food Safety Authority for food coloring (Albuquerque et al. 2021). There is still a long way to take full advantages of their bioactive functions of the wide range of phenolics in berry species. Meanwhile, berry cultivation and related industrial processing inevitably result in tons of by-products/side-streams (such as leaves, stems, and pomaces), which are also rich in phenolics. From the point of view of sustainable economy, extraction and application of phenolic compounds is an important way to valorize the side-streams of production and processing of Nordic berries.

In food industry, using synthetic preservatives is an essential and effective way to protect food components from oxidation and to prevent the growth of foodborne pathogens, extending the shelf life of food products. The commonly-applied preservatives are nitrites (E249–E250), nitrates (E251–E252), acetic acid (E260), lactic acid (E270), butylated hydroxyanisole (BHA, E320), butylated hydroxytoluene (E321), tert-butylhydroquinone (E319), and propyl gallate (PG, E310). The usage of these additives in food products is strictly regulated to ensure the food safety and consumer protection. Despite this, consumers are increasingly concerned about the safety of these synthetic food preservatives. Therefore, there is a strong interest in food industry for development and application of preservatives from natural sources.

Previous review articles have revealed the potential of natural plants to protect sensitive ingredients in foods and to extend shelf-life of food products (Ahmad et al. 2015; Efenberger-Szmechtyk, Nowak, and Czyzowska 2021). These protective effects are attributed to the bioactive compounds present in plant extracts, of which phenolic compounds form a major group responsible for the anti-microbial and anti-oxidative activities (Shah, Bosco, and Mir 2014; Efenberger-Szmechtyk, Nowak, and Czyzowska 2021). As anti-bacterial agents, phenolic compounds are able to (1) react with cell membrane and increase the permeability causing breaking-down of cell; (2) deactivate essential enzymes related to DNA and RNA synthesis (Efenberger-Szmechtyk, Nowak, and Czyzowska 2021). For inhibiting oxidation, phenolics have been shown to (1) directly scavenge free radicals, (2) chelate metal cations, (3) activate anti-oxidative enzymes, and (4) inhibit oxidases (Aziz and Karboune 2018).

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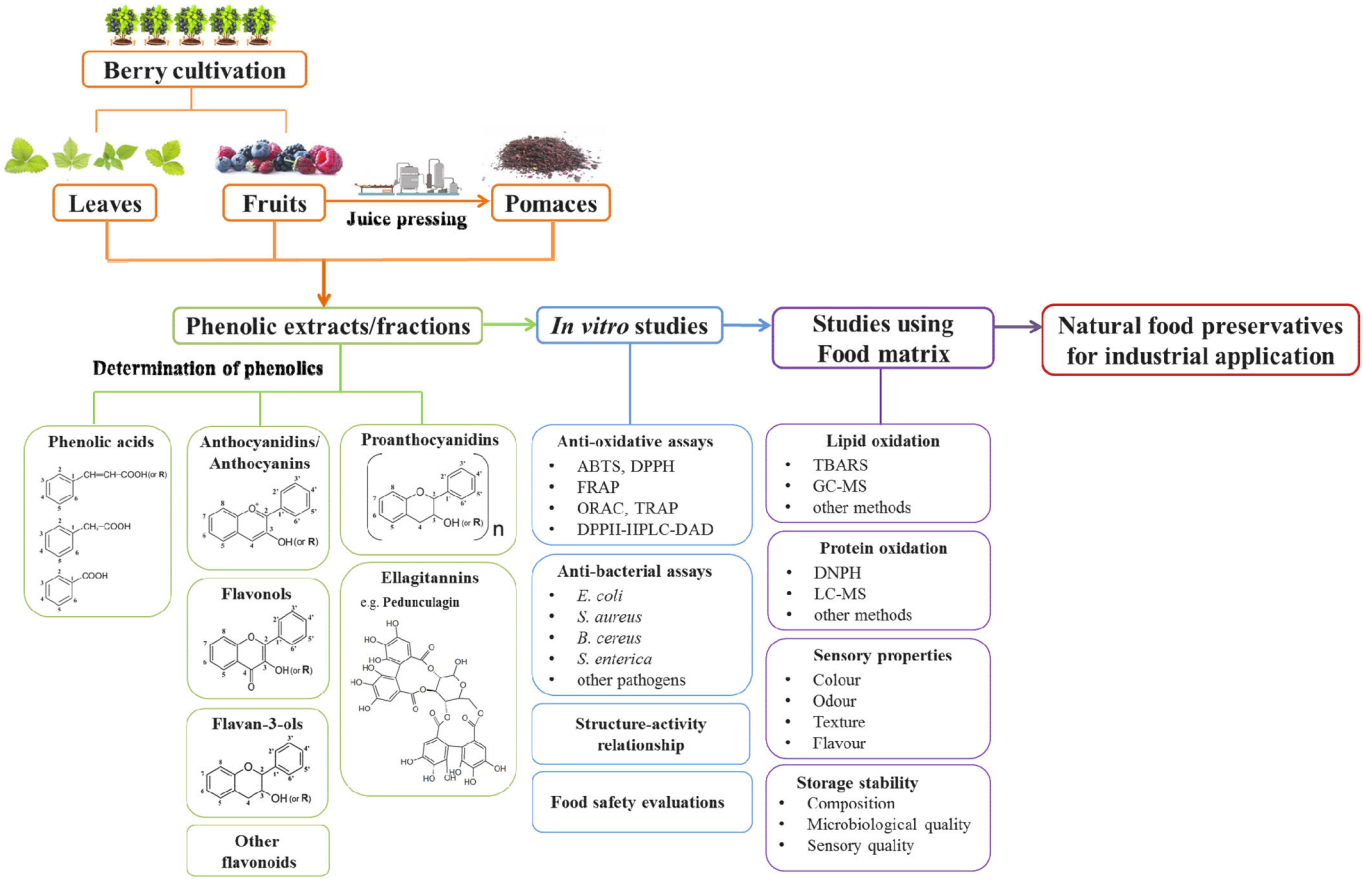


Figure 1. Scheme of fruits and side-streams of berry species applying as potential food preservatives. 2,2′-azino-bis(3-ethylbenzothiazoline-6-sulphonic acid) assay (ABTS), 2,2-diphenyl-1-picrylhydrazyl assay (DPPH), oxygen radical absorbance capacity assay (ORAC), total radical trapping antioxidant parameter assay (TRAP), high-performance liquid chromatography (HPLC), diode-array detector (DAD), *Escherichia coli* (*E. coli*), *Staphylococcus aureus* (*S. aureus*), *Bacillus cereus* (*B. cereus*), *Salmonella enterica* (*S. enterica*), thiobarbituric acid reagent substances assay (TBARS), gas/liquid chromatography (GC/LC), mass spectrometry (MS), and 2,4-dinitrophenylhydrazine assays (DNPH).

Among plant extracts studied, fruit extracts of berry species have also been applied in meat products as natural antioxidants. As reviewed by Lorenzo et al. (2018), addition of fruit extracts of bearberry (*Arctostaphylos uva-ursi*), blackberry (*Rubus fruticosus*), blackcurrant (*Ribes nigrum*), cranberry (*Vaccinium oxycoccus*), cloudberry (*Rubus chamaemorus*), and strawberry (*Fragaria* × *ananassa*) results in reduction in oxidation of lipids, proteins, and pigments during the storage of meat products. Das et al. (2017) have reviewed inhibitory efficacy of phenolic extracts of berry species on the growth of various foodborne bacterial strains, such as *Listeria* genus, *Staphylococcus aureus*, *Clostridium perfringens*, *Salmonella enterica*, *Escherichia coli*, and *Campylobacter* spp. In the recent years, more research interests have been directed toward leaves and stems of berry species, and pomaces after juice-pressing, the extracts of which also showed potent capacities against oxidation and various foodborne pathogens both *in vitro* and in meat products.

Nevertheless, successful application of berry species as natural food preservatives is not dependent only on potent anti-oxidative and anti-bacterial effects. Acceptance from consumers also plays an important role. Addition of berry-derived extracts may influence the orosensory of meat products, since certain compounds in the extracts have been reported to contribute to negative flavors (Laaksonen et al. 2013). This has not drawn enough attention in current research. Numerous *in vitro* assays suggest that the anti-oxidative and anti-bacterial potency of extracts from various berry species is significantly influenced by many factors causing variation in phenolic profiles. Furthermore, interaction between berry extracts and food matrix plays an important role in influencing both the efficacies of food preservation and the sensory qualities of the food products.

Therefore, in order to explore the industrial application of berry species, especially the valorization of side-streams of berry cultivation and juice-pressing industry, the present review takes the common Nordic berry species as examples, and provides systematic review of the current literature on key issues related to application of berry species as natural food preservatives. Special attention is placed on leaves and pomaces of berry species. Following the scheme presented in Figure 1, this article starts with introducing phenolic profiles of different extracts of Nordic berry species. The bioactivities of phenolic extracts directly linked to food preservation, such as anti-oxidative and anti-bacterial activities, are reviewed, as well as the factors influencing the bioactivities of the extracts. This review also examines individual berry phenolics mainly responsible for the bioactivities and the impact of their chemical structures on studied bioactivities. Eventually, the review summarizes the current application of phenolic extracts of Nordic berry species as meat

preservatives. The limitation of these studies is discussed carefully and some suggestion is given to future industrial application of Nordic berry species.

Phenolic compounds in Nordic berry species

Phenolics in berry plants are generally characterized as flavonoids and non-flavonoid compounds. Table 1 shows the general composition of phenolics in different extracts (fruits, pomaces, and leaves) of common berry species. The deviation in the phenolic contents among previous studies is likely the outcome of complex interplay of multiple factors including subspecies, cultivation, climatic condition, ripeness stage, harvesting time, extraction methods, and even the selection of quantification standards. Within the same berry species, the variation of phenolic composition between leaves and fruits has been shown in our previous study (Tian et al. 2017). To eliminate the impact of factors mentioned above, the studied materials were cultivated, collected, and extracted under same condition. The phenolic profiles of different parts of selected berry species are presented in Figure 2 (berries) and Figure 3 (leaves).

Flavonoid compounds present in the extracts of berry species mainly as anthocyanins, flavonols, and flavan-3-ols. Anthocyanins are predominant phenolic compounds in dark-skinned berries, responsible for the blue, purple, and red colors of berries. Compared to fruits, anthocyanins are absent in the most of leaves of berry plants. However, some of *Vaccinium* plants (such as bilberry, *V. myrtillus*; blueberry, *V. corymbosum*, *V. ashei*; and cranberry, *V. macrocarpon*) have been found to contain low amounts of anthocyanins in the leaves of certain cultivars/varieties. The main groups of anthocyanins are delphinidin, cyanidin, petunidin, peonidin, pelargonidin, and malvidin primarily as 3-*O*-glycosides (rutinoside, galactoside, glucoside, and arabinoside, Figure 2), present with varying abundance among different berry species (Veberic et al. 2015). Flavonols form the most dominant group of flavonoids in light-colored fruits that lack anthocyanins, such as sea buckthorn (*Hippophaë rhamnoides*). For leaves of berry species, high levels of flavonols are present in leaf extracts of bilberry, blueberry, cranberry, lingonberry (*Vaccinium vitis-idaea*), and saskatoon (*Amelanchier alnifolia*) (Table 1). Flavonols in berry species are usually *O*-glycosylated with rutinose, glucose, galactose, rhamnose, arabinose, xylose, and glucuronic acid (Figures 2 and 3). Some of these sugar moieties are found acylated with acetic acid, coumaric acid, and malonic acid. Although the flavonol profile varies among different extracts of berry species, quercetins are the most abundant sub-group (Dudonné et al. 2015). Both fruits and leaves of sea buckthorn are rich in isorhamnetins (Ma et al. 2021). Derivatives of myricetin and kaempferol are abundant in fruits and leaves of blackcurrant, respectively (Tian et al. 2017; Tian et al. 2019). Other minor groups of flavonols, such as laricitrin or syringetin, are detected in the extracts of crowberry (*Empetrum nigrum*), blueberry, bilberry, and gooseberry (*Ribes grossularia*), generally at low levels (Mikulic-Petkovsek et al. 2012; Tian et al. 2017). Flavan-3-ols are more concentrated in leaves compared to fruits. The rich sources of flavan-3-ols include the leaves of bilberry, hawthorn (*Crataegus* spp.), lingonberry, saskatoon, and sea buckthorn (Table 1).

In berry species, non-flavonoid compounds consist mainly of phenolic acids and tannins. Phenolic acids, as shown in Table 1, are dominant in leaves of *Vaccinium* spp. (bilberry, blueberry, and lingonberry). The pool of phenolic acids in berry plants includes hydroxycinnamic acid and hydroxybenzoic acid, such as coumaric acid, caffeic acid, ferulic acid, *p*-hydroxybenzoic acid, gallic acid, and protocatechuic acids. Most of the phenolic acids are present either in the free form or as esterified derivatives with sugars or other acids. Tannins include proanthocyanidins and hydrolyzable tannins. The former group, commonly known as condensed tannins, belongs to polymeric flavan-3-ols; the latter mainly consists of gallotannins (mostly as esterified glucoses with gallic acids) and ellagitannins (glucose esters of gallic acid and ellagic acid). Both proanthocyanidins and hydrolyzable tannins exhibit a wide structural variability, which is associated with the different linkages between monomeric units, and the degree of polymerization. Among common berry species, cranberry, hawthorn, lingonberry, and saskatoon are known for abundance of proanthocyanidins (mainly procyanidins) in both fruits and leaves (Table 1). The leaves of bilberry and the fruits of blackcurrant and sea buckthorn also contain significant amounts of procyanidins (Ștefănescu et al. 2020; Yang et al. 2016, 2019). High contents of ellagitannins have been quantified from blackberries, raspberries (*Rubus idaeus*), and strawberries, as well as their corresponding leaves (Table 1). The major ellagitannins in *Rubus* species are lambertianin C and sanguiin H-6; pedunculagin, potentillin, casuarictin, agrimoniin, and Fragariin A being dominant in strawberry (Klewicka et al. 2016; Karlińska et al. 2021). Leaves of cloudberry and sea buckthorn are also rich in ellagitannins. Cloudberry leaves mainly contain sanguiin H-6 and lambertianin C, whereas stachyurin, casuarictin, hippophaenin B, and casuarinin are primary ellagitannins in sea buckthorn leaves (Moilanen, Koskinen, and Salminen 2015).

Anti-oxidative activities of phenolic extracts of Nordic berry species

The inhibitory activities of fruit extracts from different berry species against oxidation have been studied extensively. Phenolic compounds are commonly considered to be responsible for antioxidant capacity of these extracts due to strong correlation between content of total phenolics and results of anti-oxidative measurement. Table 2 summarizes some recent studies on *in vitro* anti-oxidative capacities of extracts of common berry species (including fruits, leaves, branches, juices, and pomaces). In these studies, multiple *in vitro* assays based on different mechanisms are applied to evaluate anti-oxidative efficacies. The content and profile of phenolics vary among the extracts of different berry species, as well as between extracts of fruits and leaves. Each group of phenolics exerts varying efficacies in different anti-

Table 1. Contents of some main groups of phenolic compounds in extracts of certain berry species measured by HPLC.

		Content (mg/100 g of studied materials, fresh/dry weight, FW/DW)							
Berry species	Extraction	Flavan-3-ols	Proanthocyanidins	Ellagitannins	Phenolic acids	Flavonols	Anthocyanins	Others	Literature
Bilberry (fruit)	Ethanol/water/acetic acid (70:29:1, vol/vol/vol)	—	—	—	—	30 (FW)	534 (FW)	—	Tian et al. 2017
	Methanol/BHT/formic acid (97:1:3, vol/wt/vol)	—	—	—	—	18 (FW)	772 (FW)	—	Veberic et al. 2015; Mikulic-Petkovsek et al. 2012
Bilberry (leaf)	Ethanol/water (40:60, vol/vol)	1022–3638 (DW)	1879–3643 (DW)	—	5556–6559 (DW)	6381–7255 (DW)	61–88 (DW)	—	Ștefănescu et al. 2020
	Ethanol/water/acetic acid (70:29:1, vol/vol/vol)	43 (FW)	111 (FW)	—	1358 (FW)	152 (FW)	—	—	Tian et al. 2017
Blackcurrant (fruit, green)	Methanol/hydrochloric acid (99:1, vol/vol) and ethyl acetate	12–20 (DW)	—	—	16–39 (DW)	18–41 (DW)	—	2–4 (DW)	Tian et al. 2019
	Ethanol/water/acetic acid (70:29:1, vol/vol/vol)	13 (FW)	—	—	37 (FW)	19 (FW)	—	3 (FW)	Tian et al. 2017
Blackcurrant (fruit, black)	Methanol/hydrochloric acid (99:1, vol/vol) and ethyl acetate	10–23 (DW)	—	—	8–37 (DW)	18–60 (DW)	532–2703 (DW)	0–5 (DW)	Tian et al. 2019
	Acetone/water/acetic acid (80:19.5:0.5, vol/vol/vol)	—	1072–1465 (DW)	—	—	—	—	—	Yang et al. 2019
	Methanol/BHT/formic acid (97:1:3, vol/wt/vol)	—	—	—	—	20 (FW)	66 (FW)	—	Veberic et al. 2015; Mikulic-Petkovsek et al. 2012
Blackcurrant (pomace, black)	Ethanol/water/acetic acid (70:29:1, vol/vol/vol)	—	—	—	9 (FW)	34 (FW)	337 (FW)	—	Tian et al. 2017
Blackcurrant (leaf, green)	Ethanol/water/acetic acid (70:29:1, vol/vol/vol)	29 (FW)	—	—	24 (FW)	490 (FW)	—	—	Tian et al. 2017
Blackcurrant (leaf, black)	Ethanol/water/acetic acid (70:29:1, vol/vol/vol)	19 (FW)	—	—	82 (FW)	492 (FW)	—	—	Tian et al. 2017
	Ethanol/water (50:50, vol/vol) containing 0.05 M H_3PO_4	1–2 (DW)	—	—	13–56 (DW)	176–720 (DW)	—	—	Vagiri et al. 2015
Blueberry (fruit)	Ethanol	0–2 (FW)	24–4 (FW)	—	7–52 (FW)	20–100 (FW)	69–102 (FW)	—	Dudonné et al. 2015
	Methanol/BHT/formic acid (97:1:3, vol/wt/vol)	—	—	—	—	19 (FW)	271 (FW)	—	Veberic et al. 2015; Mikulic-Petkovsek et al. 2012
Blueberry (leaf)	Methanol/formic acid (98:2, vol/vol)	—	34–838 (DW)	—	1137–8455 (DW)	551–3389 (DW)	0–404 (DW)	0–615 (DW)	Wang, Wu, et al. 2015
Chokeberry (fruit)	Ethanol/water/acetic acid (70:29:1, vol/vol/vol)	—	—	—	248 (FW)	61 (FW)	402 (FW)	—	Tian et al. 2017
	Ethanol	trace	81 (FW)	—	64 (FW)	49 (FW)	357 (FW)	—	Dudonné et al. 2015
	Methanol/BHT/formic acid (97:1:3, vol/wt/vol)	—	—	—	—	27 (FW)	401 (FW)	—	Veberic et al. 2015; Mikulic-Petkovsek et al. 2012
Chokeberry (leaf)	Ethanol/water/acetic acid (70:29:1, vol/vol/vol)	—	—	—	182 (FW)	309 (FW)	—	77 (FW)	Tian et al. 2017
Cloudberry (fruit)	Ethanol	8 (FW)	4 (FW)	—	6 (FW)	12 (FW)	2 (FW)	—	Dudonné et al. 2015
Cranberry (fruit)	Methanol/water/hydrochloric acid (80:19:1, vol/vol/vol)	38 (DW)	1900 (DW)	—	425 (DW)	1179 (DW)	8110 (DW)	109 (DW)	Oszmiański et al. 2016

	Ethanol	135 (FW)	703 (FW)	—	139 (FW)	8 (FW)	30 (FW)	—	Dudonné et al. 2015
	Methanol/BHT/formic acid (97:1:3, vol/wt/vol)	—	—	—	—	21 (FW)	25 (FW)	—	Veberic et al. 2015; Mikulic-Petkovsek et al. 2012
Cranberry (pomace)	Ethanol/water/acetic acid (70:29:1, vol/vol/vol)	—	—	—	—	40 (FW)	83 (FW)	51 (FW)	Tian et al. 2017
	Methanol/water/hydrochloric acid (80:19:1, vol/vol/vol)	46 (DW)	2387 (DW)	—	458 (DW)	1477 (DW)	10,783 (DW)	56 (DW)	Oszmiański et al. 2016
Cranberry (leaf)	Methanol/water/hydrochloric acid (80:19:1, vol/vol/vol)	416 (DW)	3804 (DW)	—	1058 (DW)	16,520 (DW)	2601 (DW)	471 (DW)	Oszmiański et al. 2016
Crowberry (fruit)	Ethanol/water/acetic acid (70:29:1, vol/vol/vol)	—	—	—	27 (FW)	57 (FW)	349 (FW)	—	Tian et al. 2017
	Ethanol	10 (FW)	71 (FW)	—	12 (FW)	27 (FW)	503 (FW)	—	Dudonné et al. 2015
Elderberry (fruit)	Ethanol	—	40 (FW)	—	19 (FW)	—	211 (FW)		Dudonné et al. 2015
	Methanol/BHT/formic acid (97:1:3, vol/wt/vol)	—	—	—	—	45–57 (FW)	204–802 (FW)		Veberic et al. 2015; Mikulic-Petkovsek et al. 2012
Hawthorn (fruit)	Ethanol/water/acetic acid (70:29:1, vol/vol/vol)	125 (FW)	206 (FW)	—	71 (FW)	14 (FW)	18 (FW)	7 (FW)	Tian et al. 2017
	Methanol/BHT/formic acid (97:1:3, vol/wt/vol)	—	—	—	—	10–12 (FW)	25–26 (FW)	—	Veberic et al. 2015; Mikulic-Petkovsek et al. 2012
Hawthorn (leaf)	Ethanol/water/acetic acid (70:29:1, vol/vol/vol)	193 (FW)	235 (FW)	—	140 (FW)	471 (FW)	—	161 (FW)	Tian et al. 2017
Lingonberry (fruit)	Ethanol/water/acetic acid (70:29:1, vol/vol/vol)	112 (FW)[a]	39 (FW)	—	210 (FW)	31 (FW)	48 (FW)	—	Tian et al. 2017
	Ethanol	1 (FW)	253 (FW)	—	26 (FW)	trace	223 (FW)	—	Dudonné et al. 2015
	Methanol/BHT/formic acid (97:1:3, vol/wt/vol)	—	—	—	—	9 (FW)	48 (FW)	—	Veberic et al. 2015; Mikulic-Petkovsek et al. 2012
Lingonberry (leaf)	Ethanol/water (40:60, vol/vol)	7497–10,435 (DW)	2150–2972 (DW)	—	2896–4146 (DW)	2275–3676 (DW)	—	—	Ștefănescu et al. 2020
	Ethanol/water (60:40, vol/vol)	17–353 (DW)	141–839 (DW)	—	41–198 (DW)	545–1398 (DW)	—	707–5697 (DW)	Raudone et al. 2019
	Ethanol/water/acetic acid (70:29:1, vol/vol/vol)	1178 (FW)	850 (FW)	—	399 (FW)	999 (FW)	—	2711 (FW)	Tian et al. 2017
Raspberry (fruit)	Methanol/BHT/formic acid (97:1:3, vol/wt/vol)	—	—	—	—	3 (FW)	75–81 (FW)	—	Veberic et al. 2015; Mikulic-Petkovsek et al. 2012
Raspberry (pomace)	Methanol/water (50:50, vol/vol)	—	—	86,287 (FW)	—	—	—	—	Klewicka et al. 2016
Raspberry (leaf)	Ethanol/water/acetic acid (70:29:1, vol/vol/vol)	—	—	1493 (FW)	—	690 (FW)	—	—	Tian et al. 2017
Redcurrant (fruit, *white*)	Ethanol/water/acetic acid (70:29:1, vol/vol/vol)	4 (FW)	—	—	15 (FW)	4 (FW)	—	9 (FW)	Tian et al. 2017
Redcurrant (fruit, *red*)	Ethanol/water/acetic acid (70:29:1, vol/vol/vol)	1 (FW)	—	—	10 (FW)	3 (FW)	8 (FW)	6 (FW)	Tian et al. 2017

(*continued*)

Table 1. Continued.

Berry species	Extraction	Content (mg/100 g of studied materials, fresh/dry weight, FW/DW)							Literature
		Flavan-3-ols	Proanthocyanidins	Ellagitannins	Phenolic acids	Flavonols	Anthocyanins	Others	
	Methanol/BHT/formic acid (97:1:3, vol/wt/vol)	—	—	—	—	0–5 (FW)	18 (FW)	—	Veberic et al. 2015; Mikulic-Petkovsek et al. 2012
Redcurrant (leaf, *white*)	Ethanol/water/acetic acid (70:29:1, vol/vol/vol)	24 (FW)	—	—	65 (FW)	364 (FW)	—	97 (FW)	Tian et al. 2017
Redcurrant (leaf, *red*)	Ethanol/water/acetic acid (70:29:1, vol/vol/vol)	—	—	—	45 (FW)	516 (FW)	—	—	Tian et al. 2017
Rowanberry (fruit)	Ethanol/water/acetic acid (70:29:1, vol/vol/vol)	3 (FW)	3 (FW)	—	237 (FW)	34 (FW)	5 (FW)	—	Tian et al. 2017
	Methanol/BHT/formic acid (97:1:3, vol/wt/vol)	—	—	—	—	23 (FW)	20 (FW)	—	Veberic et al. 2015; Mikulic-Petkovsek et al. 2012
Saskatoon (fruit)	Methanol/water/ascorbic acid/acetic acid (30:69:2:1, vol/vol/wt/vol)	12–89 (DW)	1210–2790 (DW)	—	465–1397 (DW)	195–375 (DW)	914–1967 (DW)	—	Lachowicz et al. 2017
	Ethanol/water/acetic acid (70:29:1, vol/vol/vol)	—	—	—	272 (FW)	56 (FW)	222 (FW)	—	Tian et al. 2017
	Ethanol	trace	12 (FW)	—	25 (FW)	17 (FW)	76 (FW)	—	Dudonné et al. 2015
Saskatoon (leaf)	Ethanol/water/acetic acid (70:29:1, vol/vol/vol)	91 (FW)	233 (FW)	—	543 (FW)	669 (FW)	—	—	Tian et al. 2017
Sea buckthorn (fruit)	Methanol/water (30:70, vol/vol)	5–17 (DW)	—	—	2–5 (DW)	—	—	—	Sytařová et al. 2020
	Ethanol/water/acetic acid (70:29:1, vol/vol/vol)	—	—	—	—	77–86 (FW)	—	—	Tian et al. 2017
	Acetone/water (80:20, vol/vol)	9–16 (DW)	—	—	38–98 (DW)	330–483 (DW)	—	—	Guo, Guo, et al. 2017
	Acetone/water/acetic acid (80:19.5:0.5, vol/vol/vol)	—	390–1940 (DW)	—	—	—	—	—	Yang et al. 2016
Sea buckthorn (pomace)	Ethyl acetate	—	—	—	7 (FW)	36 (FW)	—	—	Damerau et al. 2020
	Pressurized ethanol and water	5–8 (DW)	1–3 (DW)	—	—	13–70 (DW)	—	6–9 (DW)	Dienaitė et al. 2020
Sea buckthorn (leaf)	Methanol/water (30:70, vol/vol)	68–379 (DW)	—	—	79–489 (DW)	—	—	—	Sytařová et al. 2020
	Acetone/water (70:30, vol/vol)	—	—	2920–3251 (DW)	—	131–141 (DW)	—	—	Ma et al. 2019
	Acetone/water (70:30, vol/vol)	—	—	4250–10,910 (DW)	—	—	—	—	Suvanto et al. 2018
	Ethanol/water/acetic acid (70:29:1, vol/vol/vol)	218–255 (FW)	—	5482–7302 (FW)	—	310–339 (FW)	—	—	Tian et al. 2017
Strawberry (fruit)	Acetone/water/formic acid (70/29.9/0.1, vol/vol/vol)	—	—	296–1856 (DW)	—	—	—	—	Karlińska et al. 2021
	Methanol/BHT/formic acid (97:1:3, vol/wt/vol)	—	—	—	—	1–3 (FW)	100–112 (FW)	—	Veberic et al. 2015; Mikulic-Petkovsek et al. 2012
Strawberry (leaf)	Acetone/water/formic acid (70/29.9/0.1, vol/vol/vol)	—	—	3318–15,178 (DW)	—	—	—	—	Karlińska et al. 2021
	Ethanol/water (80/20, vol/vol)	20 (DW)	—	—	2171 (DW)	267 (DW)	—	—	Mekinić et al. 2019

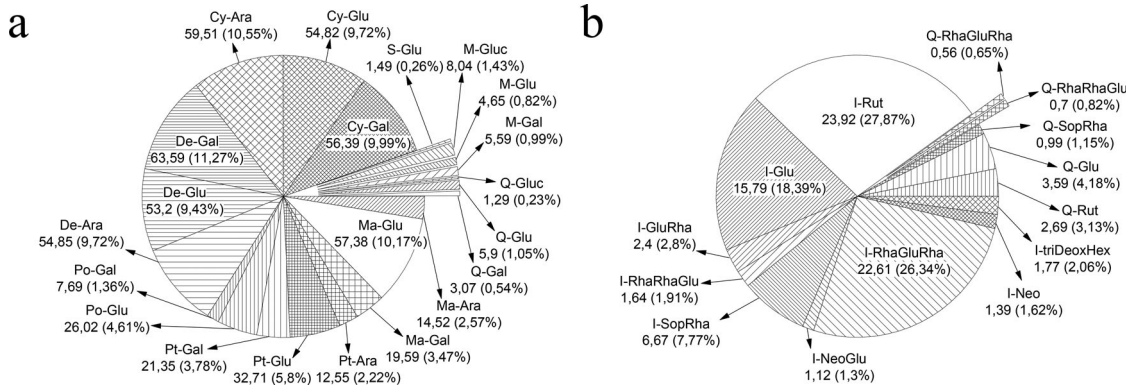


Figure 2. Examples of major phenolic composition of berry extracts of Nordic berry species (cited from Tian et al. 2017). Note: a. bilberry; b. sea buckthorn. Quercetin (Q), myricetin (M), isorhamnetin (I), syringetin (S), cyanidin (Cy), delphinidin (De), petunidin (Pt), peonidin (Po), malvidin (Ma), rutinoside (Rut), galactoside (Gal), glucoside (Glu), hexoside (Hex), rhamnoside (Rha), deoxyhexoside (Deox), arabinoside (Ara), glucuronide (Gluc), neohesperidoside (Neo), and sophoroside (Sop).

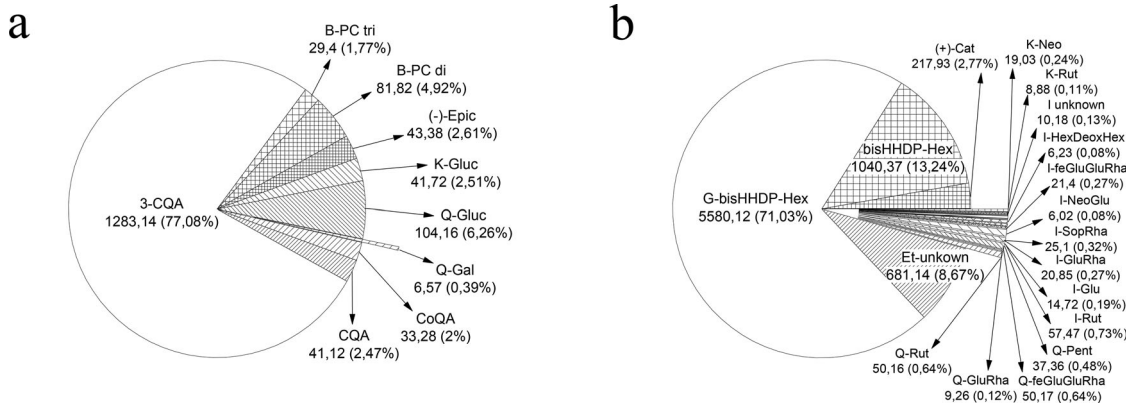


Figure 3. Examples of major phenolic composition of leaf extracts of Nordic berry species (cited from Tian et al. 2017). Note: a. bilberry leaf; b. sea buckthorn leaf. (+)-catechin ((+)-Cat), (−)-epicatechin ((−)-Epic), B-type procyanidin dimers/trimers (B-PC di/tri), bis(hexahydroxydiphenoyl)-hexoside (bisHHDP-Hex), ellagitannin (Et), galloyl-bis(hexahydroxydiphenoyl)-hexoside (G-bisHHDP-Hex), coumaroylquinic acid (CoQA), 3-*O*-caffeoylquinic acid (3-CQA), quercetin (Q), isorhamnetin (I), kaempferol (K), rutinoside (Rut), galactoside (Gal), glucoside (Glu), hexoside (Hex), rhamnoside (Rha), deoxyhexoside (Deox), pentoside (Pent), glucuronide (Gluc), feruloyl-glucoside (feGlu), neohesperidoside (Neo), and sophoroside (Sop).

oxidative assays. This explains why antioxidant activities of extracts from different berry species and materials vary among the assays applied.

Compared to fruits, leaves and pomaces of berry species have also shown considerably high inhibitory efficacy against free radical-induced oxidation. Bujor and coworkers collected leaves and stems of bilberry in May, July, and September of two consecutive years, and evaluated their abilities of scavenging free radicals by 2,2-diphenyl-1-picryl-hydrazyl (DPPH) assay. Regardless of seasonal variation, DPPH radical scavenging capacities of aqueous methanol extracts of both leaves and stems were significantly higher than that of ripe bilberries collected in June of each of the studied years. The antioxidant activity in the DPPH test was highly associated with total content of phenolics measured by both lipid chromatographic (LC) and Folin-Ciocalteu method (Bujor et al. 2016). Later, Bujor et al. (2018) studied leaf and stem extracts of lingonberry using same antioxidant assay. The leaf and stem extracts also showed higher efficacies in DPPH radical scavenging, which was over 4-fold stronger than the activities of fruit extract of lingonberry. As shown in Table 2, Tian, Puganen, et al. (2018) investigated the *in vitro* anti-oxidative capacities of leaves and berries of thirteen Finnish berry plants. Oxygen radical absorbance capacity (ORAC) and total radical trapping antioxidant parameter (TRAP) suggested that the acidified ethanolic extracts of leaves were better peroxyl-radical scavengers than those of berries. The extracts of lingonberry leaf had the highest ORAC and TRAP values of 463 and 108 Trolox equivalent (TE) mg/g fresh leaves, respectively. The phenolic extracts of hawthorn leaf, bilberry leaf, saskatoon leaf, and sea buckthorn leaf were also potent hydrogen donators. For berry extracts, those of chokeberries, lingonberries, and bilberries had the highest ORAC (39–46 TE mg/g fresh berries) and TRAP (12–14) activities. In DPPH assay, over 80% of DPPH radicals were trapped by most of the leaf extracts within 10 min, among which, two sea buckthorn leaf extracts scavenged almost 90% radicals during the first 30 s of analysis. In contrast, the best DPPH scavengers among berry extracts are the pomace of chokeberry and blackcurrant capturing 80% radicals in 10 mins, but the scavenging ability of other berry extracts was low (30%–50%). Similar with berries, juice-pressing pomaces are potent antioxidants as reported recently. de Souza et al. (2019) evaluated saskatoon berries of three varieties and commercial saskatoon pomace with 2,2′-azino-bis(3-ethylbenzothiazoline-6-sulphonic acid)

Table 2. Previous studies on *in vitro* anti-oxidative activities of phenolic compounds of berry species.

Common name	Latin name	Subject	Extraction	Phenolic compounds	Results	Literature
Bilberry	*Vaccinium myrtillus*	Fruit leaf	70% ethanol containing 1.0% acetic acid	Total phenolics[a] phenolic acids[c] flavonoids[c] tannins[c]	Fruit: 22–66, leaf: 28–92 (% inhibition, DPPH) fruit: 39, leaf: 121 (mg TE/g FW, ORAC) fruit: 12, leaf: 65 (mg TE/g FW, TRAP)	Tian, Puganen, et al. 2018
	Vaccinium myrtillus	Fruit	Water 70% acetone 70% methanol	Total phenolics[a] total anthocyanins[b] anthocyanins[c] phenolic acids[c]	8–133 (μmol TE/g DW, ABTS) 20–141 (μmol TE/g DW, FRAP) 14–123 (μmol TE/g DW, ORAC)	Colak et al. 2017
Blackcurrant	*Ribes nigrum* cv. "Mortti"	Pomace	92% ethanol	Total phenolics[a]	21–90 (% inhibition, DPPH) 22–89 (μmol TE/g FW, ORAC) 2–26 (μmol TE/g FW, TRAP)	Puganen et al. 2018
	Ribes nigrum cv. "Vertti" (green)	Pomace	92% ethanol	Total phenolics[a]	11–95 (% inhibition, DPPH) 6–33 (μmol TE/g FW, ORAC) 1–9 (μmol TE/g FW, TRAP)	Puganen et al. 2018
	Ribes nigrum cv. "Mortti"	Pomace	70% ethanol containing 1.0% acetic acid	Total phenolics[a] phenolic acids[c] flavonoids[c] tannins[c]	29–83 (% inhibition, DPPH) 30 (mg TE/g FW, ORAC) 6 (mg TE/g FW, TRAP)	Tian, Puganen, et al. 2018
	Ribes nigrum cv. "Vertti" (green)	Leaf	70% ethanol containing 1.0% acetic acid	Total phenolics[a] phenolic acids[c] flavonoids[c] tannins[c]	42–95 (% inhibition, DPPH) 89 (mg TE/g FW, ORAC) 28 (mg TE/g FW, TRAP)	Tian, Puganen, et al. 2018
Blueberry	*Vaccinium* spp. (73 cultivars)	Leaf	85% methanol containing 0.5% formic acid	Total phenolics[a] total flavonoids[e] total proanthocyanidins[f] phenolic acids[c] flavonoids[c] tannins[c]	65–862 (μmol TE/g DW, ABTS) 144–587 (μmol TE/g DW, DPPH) 257–2674 (μmol FE/g DW, FRAP) 392–1348 (μmol TE/g DW, ORAC)	Wu et al. 2019
	Vaccinium spp. (104 cultivars)	Leaf	methanol containing 2.0% formic acid	Flavonoids[c] tannins[c]	33–256 (mg GAE/mg DW, ABTS) 10–45 (mg GAE/mg DW, DPPH) 30–139 (mg GAE/mg DW, FRAP)	Wang, Wu, et al. 2015
	Vaccinium corymbosum	Fruit	50% methanol 70% acetone	Total phenolics[a] total anthocyanins[b] total flavonoids[e]	6 (μmol/g FW, ABTS) 60 (% inhibition, β-carotene) 7775 (EC_{50}, g FW/g, DPPH)	de Souza et al. 2014
Chokeberry	*Aronia melonocarpa*	Fruit	70% ethanol containing 1.0% acetic acid	Phenolic acids[c] flavonoids[c] tannins[c]	5–17 (mg TE/mL, ORAC)	Tian, Liimatainen, et al. 2018
	Aronia melonocarpa	Fruit leaf	70% ethanol containing 1.0% acetic acid	Total phenolics[a] phenolic acids[c] flavonoids[c] tannins[c]	Fruit: 18–80, leaf: 15–59 (% inhibition, DPPH) fruit: 46, leaf: 57 (mg TE/g FW, ORAC) fruit: 14, leaf: 20 (mg TE/g FW, TRAP)	Tian, Puganen, et al. 2018
	Aronia melanocarpa cv. "Elliott"	Fruit (fresh, dried)		Total phenolics[a] total anthocyanins[b]	Fresh: 235, dried: 42–115 (mmol TE/100 g DW, ABTS) fresh: 39, dried: 2–26 (mmol TE/100 g DW, FRAP)	Samoticha et al. 2016
	Aronia mitschurinii cv. "Viking"	Juice	—	Total phenolics[a] phenolic acids[c] flavonoids[c]	0.1–0.8 (IC_{50} % juice, DPPH) 7–10 (mg TE/mL, FRAP)	Bolling et al. 2015
Cranberry	*Vaccinium macrocarpon*	Pomace				Tian, Puganen, et al. 2018

			70% ethanol containing 1.0% acetic acid	Total phenolics[a] phenolic acids[c] flavonoids[c] tannins[c]	15–44 (% inhibition, DPPH) 23 (mg TE/g FW, ORAC) 7 (mg TE/g FW, TRAP)	
	Vaccinium macrocarpon (5 genotype)	Fruit	70% acetone containing 0.5% acetic acid	Total phenolics[a] total anthocyanins[b]	31–802 (μmol TE/g DW, TEAC) 1–10 (mmol TE/g DW, ORAC) 0.09–1.12 (mmol TE/g DW, reducing power)	Abeywickrama et al. 2016
Crowberry	*Empetrum nigrum*	Fruit	70% ethanol containing 1.0% acetic acid	Phenolic acids[c] flavonoids[c] tannins[c]	5–36 (mg TE/mL, ORAC)	Tian, Liimatainen, et al. 2018
	Empetrum nigrum	Fruit	70% ethanol containing 1.0% acetic acid	Total phenolics[a] phenolic acids[c] flavonoids[c] tannins[c]	18–51 (% inhibition, DPPH) 28 (mg TE/g FW, ORAC) 7 (mg TE/g FW, TRAP)	Tian, Puganen, et al. 2018
Elderberry	*Sambucus nigra*	Fruit branch	Methanol containing 1% hydrochloric acid	Total phenolics[a] total anthocyanins[b] anthocyanins[c] flavonols[c]	Fruit: 10, branch 10 (mmol TE/100 g FW, TEAC) fruit: 93, branch 89 (% inhibition, $OH^{\bullet}$ scavenging) fruit: 190, branch 220 (mmol TE/100 g FW, $NO^{\bullet}$ scavenging)	Silva et al. 2017
Hawthorn	*Crataegus grayana*	Leaf	70% ethanol containing 1.0% acetic acid	Phenolic acids[c] flavonoids[c] tannins[c]	6–39 (mg TE/mL, ORAC)	Tian, Liimatainen, et al. 2018
	Crataegus grayana	Leaf	70% ethanol containing 1.0% acetic acid	Total phenolics[a] phenolic acids[c] flavonoids[c] tannins[c]	31–92 (% inhibition, DPPH) 143 (mg TE/g FW, ORAC) 61 (mg TE/g FW, TRAP)	Tian, Puganen, et al. 2018
	Crataegus pinnatifida (3 varieties)	Fruit	80% acetone	Total phenolics[a] total flavonoids[d] phenolic acids[c] flavonols[c] tannins[c]	0.8–1.3 (μmol QE/100 g DW, without PBS washing CAA) 1.9–2.7 (μmol QE/100 g DW, with PBS washing CAA) 398–556 (μmol TE/g DW, ORAC) 299–371 (μmol VCE /g DW, PSC)	Wen et al. 2015
Lingonberry	*Vaccinium vitis-idaea* (12 genotypes)	Leaf	60% ethanol	—	620–2180 (TE mg/g DW, ABTS) 743–1476 (TE mg/g DW, FRAP) 35–80 (% inhibition, Fe^{2+} chelating)	Raudone et al. 2019
	Vaccinium vitis-idaea	Leaf	70% ethanol containing 1.0% acetic acid	Phenolic acids[c] flavonoids[c] tannins[c]	14–113 (mg TE/mL, ORAC)	Tian, Liimatainen, et al. 2018
	Vaccinium vitis-idaea	Fruit leaf	70% ethanol containing 1.0% acetic acid	Total phenolics[a] phenolic acids[c] flavonoids[c] tannins[c]	Fruit: 7–27, leaf: 52–86 (% inhibition, DPPH) fruit: 42, leaf: 463 (mg TE/g FW, ORAC) fruit: 12, leaf: 108 (mg TE/g FW, TRAP)	Tian, Puganen, et al. 2018
Raspberry	*Rubus idaeus*	Leaf	70% ethanol containing 1.0% acetic acid	Total phenolics[a] phenolic acids[c] flavonoids[c] tannins[c]	71–94 (% inhibition, DPPH) 73 (mg TE/g FW, ORAC) 37 (mg TE/g FW, TRAP)	Tian, Puganen, et al. 2018
	Rubus idaeus	Fruit	50% methanol 70% acetone	Total phenolics[a] total anthocyanins[b] total flavonoids[e]	6 (μmol/g FW, ABTS) 75 (% inhibition, β-carotene) 4961 (EC_{50}, g FW/g, DPPH)	de Souza et al. 2014
Redcurrant		Pomace	92% ethanol	Total phenolics[a]		Puganen et al. 2018

(*continued*)

Table 2. Continued.

Common name	Latin name	Subject	Extraction	Phenolic compounds	Results	Literature
	Ribes rubrum cv. "Red Dutch"				11–94 (% inhibition, DPPH) 5–23 (μmol TE/g FW, ORAC) 1–12 (μmol TE/g FW, TRAP)	
	Ribes rubrum cv. "White Dutch" (white)	Pomace	92% ethanol	Total phenolics[a]	10–94 (% inhibition, DPPH) 5–17 (μmol TE/g FW, ORAC) 1–8 (μmol TE/g FW, TRAP)	Puganen et al. 2018
	Ribes rubrum cv. "White Dutch" (white)	Leaf	70% ethanol containing 1.0% acetic acid	Phenolic acids[c] flavonoids[c] tannins[c]	8–32 (mg TE/mL, ORAC)	Tian, Liimatainen, et al. 2018
	Ribes rubrum cv. "Red Dutch"	Leaf	70% ethanol containing 1.0% acetic acid	Total phenolics[a] phenolic acids[c] flavonoids[c] tannins[c]	29–83 (% inhibition, DPPH) 54 (mg TE/g FW, ORAC) 21 (mg TE/g FW, TRAP)	Tian, Puganen, et al. 2018
	Ribes rubrum cv. "White Dutch" (white)	Leaf	70% ethanol containing 1.0% acetic acid	Total phenolics[a] phenolic acids[c] flavonoids[c] tannins[c]	47–94 (% inhibition, DPPH) 64 (mg TE/g FW, ORAC) 21 (mg TE/g FW, TRAP)	Tian, Puganen, et al. 2018
Rowanberry	*Sorbus aucuparia*	Fruit	70% ethanol containing 1.0% acetic acid	Total phenolics[a] phenolic acids[c] flavonoids[c] tannins[c]	15–39 (% inhibition, DPPH) 22 (mg TE/g FW, ORAC) 9 (mg TE/g FW, TRAP)	Tian, Puganen, et al. 2018
Saskatoon	*Amelanchier alnifolia*	Fruit pomace	70% ethanol containing 2.0% formic acid	Phenolic acids[c] flavonoids[c]	Fruit:160–328, pomace: 305–328 (mM TE/100 mg FW, ABTS) fruit:12–23, pomace: 17–19 ($1/IC_{50}$, 1/100 mg FW, DPPH)	de Souza et al. 2019
	Amelanchier alnifolia	Leaf	70% ethanol containing 1.0% acetic acid	Phenolic acids[c] flavonoids[c] tannins[c]	15–74 (mg TE/mL, ORAC)	Tian, Liimatainen, et al. 2018
	Amelanchier alnifolia	Branch fruit leaf	70% ethanol containing 1.0% acetic acid	Total phenolics[a] phenolic acids[c] flavonoids[c] tannins[c]	Branch: 10–56, fruit: 14–52, leaf: 30–89 (% inhibition, DPPH) branch: 70, fruit: 37, leaf: 102 (mg TE/g FW, ORAC) branch: 24, fruit: 12, leaf: 42 (mg TE/g FW, TRAP)	Tian, Puganen, et al. 2018
	Amelanchier alnifolia (4 cultivars)	Fruit	30% methanol containing 2.0% ascorbic acid and 1.0% acetic acid	Phenolic acids[c] flavonoids[c] tannins[c]	9–36 (mmol TE/100 g DW, ABTS) 7–28 (mmol TE/100 g DW, FRAP)	Lachowicz et al. 2017
Sea buckthorn	*Hippophaë rhamnoides*	Pomace	pressurized ethanol and water	Total phenolics[a] flavonoids[c]	269–324 (μM TE/g DW, ABTS) 102–205 (μM TE/g DW, DPPH) 294–372 (μM TE/g DW, ORAC) 6–50 (μmol QE/mg DW, CAA)	Dienaitė et al. 2020
	Hippophaë rhamnoides cv. "Tytti"	Pomace	92% ethanol	Total phenolics[a]	6–75 (% inhibition, DPPH) 8–31 (μmol TE/g FW, ORAC) 0–6 (μmol TE/g FW, TRAP)	Puganen et al. 2018
	Hippophaë rhamnoides	Fruit leaf	70% ethanol containing 1.0% acetic acid	Phenolic acids[c] flavonoids[c] tannins[c]	Fruit: 3–10, leaf: 16–79 (mg TE/mL, ORAC)	Tian, Liimatainen, et al. 2018
	Hippophaë rhamnoides cv. "Terhi," "Tytti"	Fruit leaf	70% ethanol containing 1.0% acetic acid	Total phenolics[a] phenolic acids[c] flavonoids[c] tannins[c]	Fruit: 24–31, leaf: 90–95 (% inhibition, DPPH) fruit: 10–13, leaf: 69–78 (mg TE/g FW, ORAC)	Tian, Puganen, et al. 2018

					fruit: 2, leaf: 39–55 (mg TE/g FW, TRAP)	
	Hippophaë rhamnoides cv. "Sinensis"	Fruit	80% acetone	Total phenolics[a] phenolic acids[c] flavonoids[c]	153 (μmol TE/g FW, ORAC) 65 (μmol ASAE/g FW, PSC) 17 (μmol QE/mol, without PBS washing CAA) 7 (μmol QE/mol, with PBS washing CAA)	Guo, Chang, et al. 2017
	Hippophaë rhamnoides (4 cultivars)	Fruit	80% acetone	Total phenolics[a] total flavonoids[d] phenolic acids[c] flavonoids[c]	273–466 (μmol QE/100 g DW, without PBS washing CAA) 186–211 (μmol QE/100 g DW, with PBS washing CAA) 267–369 (μmol TE/g DW, ORAC) 148–211 (μmol VCE/g DW, PSC)	Guo, Guo, et al. 2017
Strawberry	*Fragaria* × *ananassa* cv. "Oso Grande"	Juice	microfiltration nanofiltration	Total phenolics[a] anthocyanins[c]	0–34 (mg TE/mL, ABTS) 0–7 (mg TE/mL, DPPH)	Arend et al. 2017
	Fragaria × *ananassa*	Fruit	50% methanol 70% acetone	Total phenolics[a] total anthocyanins[b] total flavonoids[e]	8 (μmol/g FW, ABTS) 67 (% inhibition, β-carotene) 3779 (EC_{50}, g FW/g, DPPH)	de Souza et al. 2014

ABTS, 2,2′-azino-bis(3-ethylbenzothiazoline-6-sulphonic acid); CAA, cellular antioxidant activity; DPPH, 2,2-diphenyl-1-picrylhydrazyl; FRAP, ferric reducing activity power; $NO^{\bullet}$, nitric oxide radical; $OH^{\bullet}$, hydroxyl radical; ORAC, oxygen radical absorbance capacity; PSC, peroxyl radical scavenging capacity; TEAC, Trolox equivalent antioxidant capacity; TRAP, total radical trapping antioxidant parameter; ASAE, ascorbic acid equivalence; EC_{50} (or IC_{50}), content causing 50% radicals scavenged (or inhibited); FE Fe^{2+} equivalence; GAE, gallic acid equivalence; QE, quercetin equivalence; TE, Trolox equivalence; VCE, Vitamin C equivalence; DW, dry weight; and FW, fresh weight.

[a]Total content of phenolics was measured by Folin–Ciocalteu assays;

[b]Total content of anthocyanins was measured by pH differential methods;

[c]Individual phenolic compounds were quantified by HPLC;

[d]Total content of flavonoids was determined by sodium borohydride/chloranil-based assay;

[e]Total content of flavonoids was determined by aluminum complex;

[f]Total content of proanthocyanidins were determined by the vanillin-hydrochloricacid method.

(ABTS) and DPPH methods. The ethanol-formic acid-water extracts of pomace represented a moderate ABTS (305 mM TE/100 mg of fresh weight) and DPPH-scavenging activities (a $1/IC_{50}$ value of 19), which was slight lower than variety "Northline," but much stronger than other two varieties. Although the authors did not study the correlation between anti-oxidative results and phenolic concentration, the overall trend of antioxidant activity was consistent with the total content of phenolics, especially total content of anthocyanins. Puganen et al. (2018) studied the methanolic extracts of press residues of sea buckthorn and (black, red, green, and white) currants using TRAP, ORAC, and DPPH assays. The extracts of blackcurrant press residues showed the highest peroxyl radical-scavenging and DPPH radical-scavenging capacities among all the samples studied, whereas the extracts of sea buckthorn residues had the lowest.

Anti-oxidative potency of berry species correlates strongly to contained phenolic compounds, thus any changes on phenolic profiles may lead to a variation of *in vitro* antioxidant activity. Abeywickrama et al. (2016) extracted phenolic compounds from Canadian cranberries (*V. macrocarpon*) of five different genotypes, and obtained three phenolic fractions from each sample, consisting of free, esterified, and bound phenolics. Ripe berries of "Pilgrim" exceeded other four clones in Trolox equivalent antioxidant capacity, ORAC, DPPH, reducing power activity, ferrous ion chelation capacity, and hydroxyl radical scavenging. The increasing trend of antioxidant capacity of this genotype was generally in proportion with the abundance of total phenolics and total flavonoids. This indicated that phenolic compounds, primarily flavonoids, are the major constituents in the cranberries responsible for their anti-oxidative activity. In addition, a large variation was shown in anti-oxidative potency of free, esterified, and bound phenolic fractions among various assays, implying the anti-oxidative roles of different groups of phenolics. Cultivating environment of berry materials is critical to their anti-oxidative activities. Puganen et al. (2018) studied two sea buckthorn pomaces, which belonged to same cultivar but was cultivated separately in southern and northern Finland. The results showed that the pomace extract of sea buckthorn berries grown in North Finland had ORAC and TRAP capacities approximately two-fold higher than that from the pomace from the southern berries. Pomace extract of the Northern berries quenched 75% of DPPH radicals in 10 min of measurement; however, the corresponding percentage of the southern counterpart was only 29%. Bolling et al. (2015) observed the harvest date influenced antioxidant activity of chokeberry juice. DPPH radical-scavenging potency of chokeberry juice was first decreased in the first three weeks of ripening, and then increased to the maximum value at the 7th week. In contrast, the activity of ferric reducing activity power (FRAP) remained increasing from week 1 to week 7.

Other factors influencing antioxidant potency of extracts of berry species have also been reported. In the study of Dienaitė et al. (2020), defatted sea buckthorn pomace was consecutive fractionated using pressurized ethanol and water. Compared to the water fraction, the ethanol fraction contained lower levels of total phenolics (measured by Folin-Ciocalteu assay), which might have resulted in its weaker efficacy in ORAC, ABTS, DPPH and cellular antioxidant activity assays. The quantitative results from LC suggested that content of flavonol glycosides in ethanol fraction was 2–9 folds more than that in water fraction. The authors assumed that flavon-3-ols gallates and tanshinlactone derivatives that concentrated in water fraction might play more important role in anti-oxidative activities than flavonols. Bustos et al. (2018) investigated the impact of air-drying conditions on antioxidant activity of raspberry, redcurrant, and blackcurrant. The ABTS and FRAP activities of raspberry were enhanced after air-drying at 65 °C, which was in accordance with the increase of polyphenol content in the dried samples measured by Folin-Ciocalteu method. The authors suggested that this increased potency might have been due to depolymerization releasing phenolics in free form. Nevertheless, it did not explain why currant samples in this study almost completely lost their anti-oxidative activity after drying at all studied temperatures. Phenolics in the studied samples might not the only compounds responsible for ABTS and FRAP activities, considering the complex chemical matrix of berries and the possibility of new compounds generated during heating.

Since most of the extracts of Nordic berry species are the complex mixture of large numbers of phenolics, it is difficult to pinpoint individual compounds contributing mostly to anti-oxidative effects. Statistical analyses are performed to discover major anti-oxidative components in extracts of berry species by determining correlation between *in vitro* anti-oxidative activities and contents of phenolic compounds. Bivariate Pearson correlation analysis has been commonly used in previous research. Multivariate statistical models, such as principal components analysis (PCA) and partial least squares regression (PLS), are recently introduced in some studies. The models are built based on the concentration of the bioactive compounds and the antioxidant activities of the extracts. Lachowicz, Oszmiański, and Pluta (2017) studied saskatoon berry of two Polish breeding clones and two Canadian cultivars using ABTS and FRAP assays. PCA model showed that anti-oxidative efficacy strongly correlated to the contents of flavonols, anthocyanins, flavan-3-ols, phenolic acid, and β-carotene, A positive but moderate correlation was observed between antioxidant activity and the contents of oleanolic acid and betulinic acid. Wu et al. (2019) characterized phenolic constituents from leaves of different blueberry cultivars. PCA models suggested the activities measured by ABTS, DPPH, FRAP, and ORAC assays highly correlated with the contents of caffeoylquinic acids and quercetin glycosides. Tian, Puganen, et al. (2018) introduced PLS models to link *in vitro* activities with over 160 phenolic compounds identified in the extracts of berries and leaves of different species. As shown by PLS models, ORAC and TRAP activities of ten berry extracts correlated positively with the concentration of glycosylated cyanidin (mainly cyanidin 3-*O*-galactoside) and quercetin (quercetin 3-*O*-galactoside). Anthocyanins (cyanidin 3-*O*-glucoside and delphinidin 3-*O*-glucoside) contributed to DPPH radical

scavenging activity. Among twelve leaf extracts studied, strong correlations were found between flavonoids and the activities measured in ORAC and TRAP assays owing to the presence of catechins, procyanidins, and quercetin monoglycosides. Ellagitannins contributed positively to DPPH radical scavenging activity. Similar results were also reported by Tian, Liimatainen, et al. (2018) studying the phenolics of leaves and fruits of berry species after fractionation with column chromatography using Sephadex LH-20. In this study, PLS models also suggested that the nature of sugar moieties correlated differently to peroxyl-radicals scavenging of flavonol glycosides. In general, the multivariate statistical models combined with thorough phenolic profiles are able to reveal the distribution of phenolic compounds in different samples and to reveal potential correlation between phenolic compounds and studied bioactivities. Nevertheless, it has to be noted that the results from multivariate statistical models only provide indications of main anti-oxidative components. The accuracy of the statistical models highly relies on numerous data, which may have explained, in some cases, the results are not in agreement with basic knowledge on the antioxidant properties of compounds. Further verification should be undertaken by isolating the targeted compounds followed by testing with various assays.

Compared to the methods of correlating bioactivities to phenolic contents, a combination of radical scavenging assay and high-performance liquid chromatography (HPLC) analysis, such as DPPH-HPLC, may be a better option to discover main compounds responsible for anti-oxidative activities of berry species extracts. Fraisse et al. (2020) studied anti-oxidative activities of bilberry by using pre-column DPPH-HPLC evaluation. The fruit extract was incubated with DPPH solvent of different contents before injected into LC system. The chromatographic analysis (monitored at wavelength of 515 nm) suggested glycosides of delphinidin, cyanidin, and petunidin (3-*O*-galacotoside, glucoside, and arabinoside) were the main contributors, due to remarkable decrease in the peak areas after incubation. In contrast, peonidins and malvidins showed minor effects on DPPH radical scavenging. Currently, this method has been rarely used to study other berry species. For disadvantages of DPPH-HPLC-DAD method, certain compounds (for examples, anthocyanidins and anthocyanins) also have strong UV absorption around 500–520 nm, which may interfere with the results. According to the studies on other plant-derived extracts, this method currently still suffers low sensitivity and resolution, especially when analyzing the extracts with complex chemical composition. A few studies suggest that it is possible to identify some unknown compounds in DPPH-treated extracts when HPLC is coupled with mass spectrometry, but more research is needed in the future (Oroian and Escriche 2015).

Anti-bacterial activities of extracts from Nordic berry species

As reported previously, extracts of bilberry, blackcurrant, chokeberry, cloudberry, cranberry, crowberry, lingonberry, raspberry, and strawberry exhibited remarkable inhibition against a wild range of bacteria, such as *Bacillus subtilis*, *Bifidobacterium lactis*, *Campylobacter jejuni*, *Enterococcus faecalis*, *Escherichia coli*, *Lactobacillus* spp., *Micrococcus luteus*, *Pseudomonas aeruginosa*, *Saccharomyces cerevisiae*, *S. enterica*, *S. aureus*, and *Staphylococcus epidermidis* (Puupponen-Pimiä et al. 2005). Leaves and pomaces have also been shown to be potent anti-pathogenic materials (Table 3). Reported by Silva et al. (2015), leaf extract of blueberry had better activity than fruit extracts in suppressing the growth of both methicillin-resistant and methicillin-sensitive *S. aureus*. Chlorogenic acid might be the primary contributor to the activity due to its abundance in both leaf and berry extracts of blueberry. Tian, Puganen, et al. (2018) investigated inhibitory effect of some common Finnish berry species against *Bacillus cereus*, *Listeria monocytogenes*, *S. aureus*, *E. coli*, and *S. enterica* sv. Typhimurium strains and revealed that the tested bacteria had varying resistance to the leaf and fruit extracts (100 mg/mL). For most of the extracts, clear inhibitory effects were found when added at dosage of 20 μL extract in 300 μL culture medium. For bilberry and chokeberry, the leaf extracts showed no inhibition against *E. coli* at low dosage (10 μL), whereas a moderate inhibition was observed from the berry extracts of these species. The strains of *B. cereus* were insensitive to all extracts of these two species at 10 μL of addition. Nevertheless, the leaf extracts of sea buckthorn and saskatoon caused stronger growth inhibition on *L. monocytogenes* and *S. aureus* than the corresponding berry extracts. Two juice-pressing residues were tested in this study. Among berry extracts, the press cakes of blackcurrant and cranberry presented the highest anti-bacterial activity against strains of *E. coli*, *L. monocytogenes*, and *S. aureus*. Bartkiene et al. (2019) reported that by-products of blackcurrant, rowanberry, and raspberry had potent activities against a range of pathogenic and opportunistic bacterial strains, although no information of the by-products were provided. All studied materials (1 g in 2 mL of the physiological solution) effectively inhibited the growth of *Acinetobacter baumannii*, *B. cereus*, *P. aeruginosa*, Methicillin-resistant *S. aureus*, *Streptococcus mutans*, *Streptococcus epidermis*, *Staphylococcus haemolyticus*, and *Pasteurella multocida* strains. Yet, only by-product of blackcurrant was active against *S. enterica*.

Based on findings of previous studies, it is not possible to conclude which berry species are more effective in anti-bacterial action, due to the deviation in methods of extraction and anti-bacterial assays applied in these studies (Table 3). The inhibitory effect is dependent on the content of phenolics in extracts, and thus changes on phenolic profile influence the anti-bacterial ability of Nordic berry species. Within a specific berry species, the inhibitory efficacy against bacteria is associated with genotypes. Criste et al. (2020) compared anti-bacterial properties of berry extract of four cultivars of sea buckthorn on *B. cereus*, *S. aureus*, and *P. aeruginosa* strains. Determined by minimum inhibitory concentration (MIC), *S. aureus* was the least sensitive to the berry extract of the cultivar "Carmen," but both *B. cereus* and *P. aeruginosa* had the strongest tolerance to "Colosal"

Table 3. Previous studies on *in vitro* anti-bacterial activities of phenolic extracts of berry species.

Common name	Latin name	Subject	Extraction	Phenolic compounds	Test methods	Results	Literature
Bilberry	*Vaccinium myrtillus*	Leaf	40% ethanol	Total phenolics[a] total flavonoids[f] total anthocyanins[c] phenolic acids[d] flavonoids[d]	Broth microdilution assay, 96 well microtiter plate method	MIC: 0.1–0.2, MBC: 0.2–0.5 (mg/mL, *Enterococcus faecalis*) MIC: 0.2–0.5, MBC: 0.5–1.0 (mg/mL, *Escherichia coli enterotoxigen*) MIC: 0.1–0.2, MBC: 0.2–0.5 (mg/mL, *Klebsiella pneumonia*) MIC: 0.2, MBC: 0.5 (mg/mL, *Pseudomonas aeruginosa*) MIC: 0.1, MBC: 0.1 (mg/mL, *Rhodococcus equi*) MIC: 0.1, MBC: 0.1–0.2 (mg/mL, *Staphylococcus aureus*)	Ștefănescu et al. 2020
	Vaccinium myrtillus	Fruit leaf	70% ethanol containing 1.0% acetic acid	Total phenolics[a] phenolic acids[d] flavonoids[d] tannins[d]	Trypticase soya agar culture coupled with spectrophotometer analysis	100 mg/mL (10 μL–20 μL extract in 300 μL culture medium) fruit: −5 to −4 leaf: −7 to 6 (% inhibition, *Bacillus cereus*) fruit: 38–58, leaf: −2 to 16 (% inhibition, *Escherichia coli*) fruit: 25–77, leaf: −4 to 43 (% inhibition, *Listeria monocytogenes*) leaf: 40–58 (% inhibition, *Salmonella enterica* sv. Typhimurium) fruit: 11–33, leaf: 28–40 (% inhibition, *Staphylococcus aureus*)	Tian, Puganen, et al. 2018
	Vaccinium myrtillus	Fruit	Water	Total phenolics[a]	96-well microplate method, broth microdilution method	MIC: 2.5, MBC: 2.5 (%, wt/vol, *Acinetobacter baumanii*) MIC: 2.5, MBC: >10 (%, wt/vol, *Bacillus cereus*) MIC: 2.5, MBC: 2.5 (%, wt/vol, *Escherichia coli* O157:H7) MIC: 1.3, MBC: 2.5 (%, wt/vol, *Listeria monocytogenes*) MIC: 5, MBC: 10 (%, wt/vol, *Pseudomonas aeruginosa*) MIC: 5, MBC: 5 (%, wt/vol, *Salmonella* Typhimurium) MIC: 5, MBC: 10 (%, wt/vol, *Shigella* flexneri) MIC: 2.5, MBC: 5 (%, wt/vol, *Shigella* sonnei) MIC: 5, MBC: 10 (%, wt/vol, *Staphylococcus aureus*) MIC: 2.5, MBC: >10 (%, wt/vol, methicillin-resistant *Staphylococcus aureus*)	Khalifa et al. 2015
Blackcurrant	*Ribes nigrum* cv. "Heifeng"	Fruit	Ammonium sulfate, water, ethanol	Flavonoids[d]	Agar diffusion assay, broth microdilution assay	MIC: 5 (mg/mL, *Escherichia coli*) MIC: 5 (mg/mL, *Salmonella* Typhimurium) MIC: 2.5 (mg/mL, *Staphylococcus aureus*)	Zhao et al. 2021
	Ribes nigrum cv. "Mortti"	Pomace	70% ethanol containing 1.0% acetic acid	Total phenolics[a] phenolic acids[d] flavonoids[d] tannins[d]	Trypticase soya agar culture coupled with spectrophotometer analysis	100 mg/mL (10 μL–20 μL extract in 300 μL culture medium) 6–77 (% inhibition, *Bacillus cereus*) 43–67 (% inhibition, *Escherichia coli*) 57–100 (% inhibition, *Listeria monocytogenes*)	Tian, Puganen, et al. 2018

						55–100 (% inhibition, *Staphylococcus aureus*)	
	Ribes nigrum	Fruit leaf	96% ethanol, water	Total anthocyanins[c] flavonoids[d]	96-well microplate method, broth microdilution method	MIC: fruit: 101–121, leaf: 156–359 (μg/mL, *Staphylococcus aureus*) MIC: fruit: 112–144, leaf: 166–307 (μg/mL, *Klebsiella pneumoniae*) MIC: fruit: 38–57, leaf: 193–389 (μg/mL, *Escherichia coli*) MIC: fruit: 96–139, leaf: 127–272 (μg/mL, *Proteus vulgaris*) MIC: fruit: 109–138, leaf: 179–320 (μg/mL, *Proteus mirabilis*) MIC: fruit: 106–139, leaf: 178–368 (μg/mL, *Bacillus subtilis*)	Paunović et al. 2017
Blueberry	*Vaccinium angustifolium*	Pomace	Water, 10% ethanol, 10% methanol	Total phenolics[a] phenolic acids[d] flavonoids[d] tannins[d]	Microdilution method	MIC: 1.5, MBC: 1.7 (mg/mL GAE, *Salmonella* Typhimurium)	Salaheen et al. 2016
	Vaccinium corymbosum	Fruit leaf	Water (100 °C)	Phenolic acids[d] anthocyanidins[d] flavonols[d]	Well diffusion assay, broth microdilution method	MIC: fruit: 50, leaf: 13; MBC: leaf: 25 (mg/mL, methicillin resistant *Staphylococcus aureus*) MIC: fruit: 50, leaf: 13; MBC: leaf: 25 (mg/mL, sensitive *Staphylococcus aureus*)	Silva et al. 2015
	Vaccinium angustifolium	Fruit	75% ethanol	Total phenolics[a] certain individual phenolics[d]	Tryptic soy agar dilution method, microdilution broth method	MIC: 300–750, MBC: 450–900 (mg/mL, *Listeria monocytogenes*) MIC: 450–1200, MBC: 600–1800 (mg/mL, *Salmonella* Enteritidis)	Shen et al. 2014
	Vaccinium formosum	Leaf	95% ethanol, 70% acetone, 100% methanol	Total phenolics[a] phenolic acids[d] flavonols[d]	Broth microdilution method	MIC: 12.5–50 (mg/mL, *Escherichia coli*) MIC: 12.5– >50 (mg/mL, *Listeria monocytogenes*) MIC: 6.3– >50 (mg/mL, *Salmonella* Typhimurium) MIC: 25– >50 (mg/mL, *Staphylococcus aureus*)	Deng et al. 2014
Chokeberry	*Aronia melonocarpa*	Fruit	70% ethanol containing 1.0% acetic acid	Phenolic acids[d] flavonoids[d] tannins[d]	Trypticase soya agar culture coupled with spectrophotometer analysis	34–93 (% inhibition, *Escherichia coli*) 49–88 (% inhibition, *Staphylococcus aureus*)	Tian, Liimatainen, et al. 2018
	Aronia melonocarpa	Fruit leaf	70% ethanol containing 1.0% acetic acid	Total phenolics[a] phenolic acids[d] flavonoids[d] tannins[d]	Trypticase soya agar culture coupled with spectrophotometer analysis	100 mg/mL (10 µL–20 µL extract in 300 µL culture medium) fruit: −82, leaf: 1–98 (% inhibition, *Bacillus cereus*) fruit: 40–59, leaf: 0–23 (% inhibition, *Escherichia coli*) fruit: 54–99, leaf: 9–89 (% inhibition, *Listeria monocytogenes*) leaf: 40–68 (% inhibition, *Salmonella enterica* sv. Typhimurium) fruit: 24–74, leaf: 53–72 (% inhibition, *Staphylococcus aureus*)	Tian, Puganen, et al. 2018
Cranberry	*Vaccinium macrocarpon*	Pomace	70% ethanol containing 1.0% acetic acid	Total phenolics[a] phenolic acids[d] flavonoids[d] tannins[d]	Trypticase soya agar culture coupled with spectrophotometer analysis	100 mg/mL (10 µL–20 µL extract in 300 µL culture medium) −1 to 89 (% inhibition, *Bacillus cereus*) 38–67 (% inhibition, *Escherichia coli*) 56–100 (% inhibition, *Listeria monocytogenes*)	Tian, Puganen, et al. 2018

(*continued*)

Table 3. Continued.

Common name	Latin name	Subject	Extraction	Phenolic compounds	Test methods	Results	Literature
						33–97 (% inhibition, *Staphylococcus aureus*)	
Crowberry	*Empetrum nigrum*	Fruit	70% ethanol containing 1.0% acetic acid	Phenolic acids[d] flavonoids[d] tannins[d]	Trypticase soya agar culture coupled with spectrophotometer analysis	12–89 (% inhibition, *Escherichia coli*) 36–80 (% inhibition, *Staphylococcus aureus*)	Tian, Liimatainen, et al. 2018
	Empetrum nigrum	Fruit	70% ethanol containing 1.0% acetic acid	Total phenolics[a] phenolic acids[d] flavonoids[d] tannins[d]	Trypticase soya agar culture coupled with spectrophotometer analysis	100 mg/mL (10 μL–20 μL extract in 300 μL culture medium) −3 to 89 (% inhibition, *Bacillus cereus*) 14–33 (% inhibition, *Escherichia coli*) 25–84 (% inhibition, *Listeria monocytogenes*) 45–77 (% inhibition, *Salmonella enterica* sv. Typhimurium) 36–66 (% inhibition, *Staphylococcus aureus*)	Tian, Puganen, et al. 2018
Hawthorn	*Crataegus grayana*	Leaf	70% ethanol containing 1.0% acetic acid	Phenolic acids[d] flavonoids[d] tannins[d]	Trypticase soya agar culture coupled with spectrophotometer analysis	31–81 (% inhibition, *Escherichia coli*) 46–84 (% inhibition, *Staphylococcus aureus*)	Tian, Liimatainen, et al. 2018
	Crataegus grayana	Leaf	70% ethanol containing 1.0% acetic acid	Total phenolics[a] phenolic acids[d] flavonoids[d] tannins[d]	Trypticase soya agar culture coupled with spectrophotometer analysis	100 mg/mL (10 μL–20 μL extract in 300 μL culture medium) 95–100 (% inhibition, *Bacillus cereus*) 20–40 (% inhibition, *Escherichia coli*) 53–100 (% inhibition, *Listeria monocytogenes*) 37–86 (% inhibition, *Salmonella enterica* sv. Typhimurium) 87–100 (% inhibition, *Staphylococcus aureus*)	Tian, Puganen, et al. 2018
Lingonberry	*Vaccinium vitis-idaea*	Leaf	40% ethanol	Total phenolics[a] total flavonoids[f] total anthocyanins[c] phenolic acids[d] flavonoids[d]	Broth microdilution assay, 96 well microtiter plate method	MIC: 0.1, MBC: 0.2 (mg/mL, *Enterococcus faecalis*) MIC: 0.5, MBC: 1.0 (mg/mL, *Escherichia coli enterotoxigen*) MIC: 0.1, MBC: 0.2 (mg/mL, *Klebsiella pneumonia*) MIC: 1.0, MBC: 2.0 (mg/mL, *Pseudomonas aeruginosa*) MIC: 0.1, MBC: 0.1 (mg/mL, *Rhodococcus equi*) MIC: 0.1, MBC: 0.2 (mg/mL, *Staphylococcus aureus*)	Ștefănescu et al. 2020
	Vaccinium vitis-idaea	Leaf	70% ethanol containing 1.0% acetic acid	Phenolic acids[d] flavonoids[d] tannins[d]	Trypticase soya agar culture coupled with spectrophotometer analysis	21–92 (% inhibition, *Escherichia coli*) 37–88 (% inhibition, *Staphylococcus aureus*)	Tian, Liimatainen, et al. 2018
	Vaccinium vitis-idaea	Fruit leaf	70% ethanol containing 1.0% acetic acid	Total phenolics[a] phenolic acids[d] flavonoids[d] tannins[d]	Trypticase soya agar culture coupled with spectrophotometer analysis	100 mg/mL (10 μL–20 μL extract in 300 μL culture medium) fruit: 23–43, leaf: 26–50 (% inhibition, *Bacillus cereus*) fruit: −3, leaf: 90–100 (% inhibition, *Escherichia coli*) fruit: 53–92, leaf: 54–37 (% inhibition,	Tian, Puganen, et al. 2018

						Listeria monocytogenes) fruit: 45–84, leaf: 54–71 (% inhibition, *Salmonella enterica* sv. Typhimurium) fruit: 43–90, leaf: 92–100 (% inhibition, *Staphylococcus aureus*)	
Raspberry	*Rubus idaeus* cv. "Kweli"	Fruit	20% ethanol	Anthocyanins[d]	Microdilution method, INT colorimetric assay	MIC: 2.5, MBC: >20 (mg/mL, *Enterococcus faecalis*) MIC: 2.5–5, MBC: >20 (mg/mL, *Escherichia coli*) MIC: >20, MBC: >20 (mg/mL, *Klebsiella pneumoniae*) MIC: 20, MBC: >20 (mg/mL, *Listeria monocytogenes*) MIC: 5–10, MBC: >20 (mg/mL, *Morganella morganii*) MIC: 20, MBC: >20 (mg/mL, *Proteus mirabilis*) MIC: 10, MBC: >20 (mg/mL, *Pseudomonas aeruginosa*) MIC: 5–10, MBC: >20 (mg/mL, methicillin-resistant *Staphylococcus aureus*)	Rocha et al. 2020
	Rubus idaeus	Leaf	70% ethanol containing 1.0% acetic acid	Total phenolics[a] phenolic acids[d] flavonoids[d] tannins[d]	Trypticase soya agar culture coupled with spectrophotometer analysis	100 mg/mL (10 μL–20 μL extract in 300 μL culture medium) 25–96 (% inhibition, *Bacillus cereus*) 16–43 (% inhibition, *Escherichia coli*) 80–100 (% inhibition, *Listeria monocytogenes*) 48–81 (% inhibition, *Salmonella enterica* sv. Typhimurium) 61–95 (% inhibition, *Staphylococcus aureus*)	Tian, Puganen, et al. 2018
	Rubus idaeus	Fruit	Water	Total phenolics[a]	96-well microplate method, broth microdilution method	MIC: 2.5, MBC: 5 (%, wt/vol, *Acinetobacter baumanii*) MIC: 5, MBC: >10 (%, wt/vol, *Bacillus cereus*) MIC: 2.5, MBC: >10 (%, wt/vol, *Escherichia coli* O157:H7) MIC: 2.5, MBC: 10 (%, wt/vol, *Listeria monocytogenes*) MIC: 5, MBC: 10 (%, wt/vol, *Pseudomonas aeruginosa*) MIC: 5, MBC: 10 (%, wt/vol, *Salmonella* Typhimurium) MIC: 5, MBC: >10 (%, wt/vol, *Shigella* flexneri) MIC: 5, MBC: >10 (%, wt/vol, *Shigella* sonnei) MIC: 5, MBC: >10 (%, wt/vol, *Staphylococcus aureus*) MIC: 5, MBC: >10 (%, wt/vol, methicillin-resistant *Staphylococcus aureus*)	Khalifa et al. 2015
Redcurrant	*Ribes rubrum* cv. "White Dutch" (white)	Leaf	70% ethanol containing 1.0% acetic acid	Phenolic acids[d] flavonoids[d] tannins[d]	Trypticase soya agar culture coupled with spectrophotometer analysis	0–92 (% inhibition, *Escherichia coli*) 53–87 (% inhibition, *Staphylococcus aureus*)	Tian, Liimatainen, et al. 2018
		Leaf					

(*continued*)

Table 3. Continued.

Common name	Latin name	Subject	Extraction	Phenolic compounds	Test methods	Results	Literature
	Ribes rubrum cv. "Red Dutch"		70% ethanol containing 1.0% acetic acid	Total phenolics[a] phenolic acids[d] flavonoids[d] tannins[d]	Trypticase soya agar culture coupled with spectrophotometer analysis	100 mg/mL (10 μL–20 μL extract in 300 μL culture medium) 1–26 (% inhibition, *Bacillus cereus*) 8–36 (% inhibition, *Escherichia coli*) 6–83 (% inhibition, *Listeria monocytogenes*) 41–67 (% inhibition, *Salmonella enterica* sv. Typhimurium) 54–77 (% inhibition, *Staphylococcus aureus*)	Tian, Puganen, et al. 2018
	Ribes rubrum cv. "White Dutch" (white)	Leaf	70% ethanol containing 1.0% acetic acid	Total phenolics[a] phenolic acids[d] flavonoids[d] tannins[d]	Trypticase soya agar culture coupled with spectrophotometer analysis	100 mg/mL (10 μL–20 μL extract in 300 μL culture medium) −3 to 90 (% inhibition, *Bacillus cereus*) 12–39 (% inhibition, *Escherichia coli*) 44–73 (% inhibition, *Listeria monocytogenes*) 50–78 (% inhibition, *Salmonella enterica* sv. Typhimurium) leaf: 49–91 (% inhibition, *Staphylococcus aureus*)	Tian, Puganen, et al. 2018
Rowanberry	*Sorbus aucuparia*	Fruit	70% ethanol containing 1.0% acetic acid	Total phenolics[a] phenolic acids[d] flavonoids[d] tannins[d]	Trypticase soya agar culture coupled with spectrophotometer analysis	100 mg/mL (10 μL–20 μL extract in 300 μL culture medium) −4 to −4 (% inhibition, *Bacillus cereus*) 22–47 (% inhibition, *Escherichia coli*) 18–72 (% inhibition, *Listeria monocytogenes*) 44–50 (% inhibition, *Salmonella enterica* sv. Typhimurium) 16–61 (% inhibition, *Staphylococcus aureus*)	Tian, Puganen, et al. 2018
Saskatoon	*Amelanchier alnifolia*	Leaf	70% ethanol containing 1.0% acetic acid	Phenolic acids[d] flavonoids[d] tannins[d]	Trypticase soya agar culture coupled with spectrophotometer analysis	0–79 (% inhibition, *Escherichia coli*) 26–98 (% inhibition, *Staphylococcus aureus*)	Tian, Liimatainen, et al. 2018
	Amelanchier alnifolia	Branch fruit leaf	70% ethanol containing 1.0% acetic acid	Total phenolics[a] phenolic acids[d] flavonoids[d] tannins[d]	Trypticase soya agar culture coupled with spectrophotometer analysis	100 mg/mL (10 μL–20 μL extract in 300 μL culture medium) branch: 4–84, fruit: −7 to −6, leaf: 67–89 (% inhibition, *Bacillus cereus*) branch: 38–68, fruit: 42–57, leaf: 53–75 (% inhibition, *Escherichia coli*) branch: 66–100, fruit: 17–74, leaf: 71–100 (% inhibition, *Listeria monocytogenes*) branch: 56–100, fruit: 16–31, leaf: 68–100 (% inhibition, *Staphylococcus aureus*)	Tian, Puganen, et al. 2018
Sea buckthorn	*Hippophaë rhamnoides*	Fruit leaf	50% ethanol	Total phenolics[a] total flavonoids[f] flavonols[d] phenolic acids[d]	96-well microplate method, broth microdilution method	MIC: fruit: 25–31, leaf: 13–25 (mg/mL, *Bacillus cereus*) MIC: fruit: 13–16, leaf: 6–13 (mg/mL, *Pseudomonas aeruginosa*) MIC: fruit: 16–25, leaf: 6–25 (mg/mL, *Staphylococcus aureus*)	Criste et al. 2020
	Hippophaë rhamnoides	Fruit leaf	70% ethanol containing 1.0% acetic acid	Phenolic acids[d] flavonoids[d] tannins[d]	Trypticase soya agar culture coupled with	fruit: 32–99, leaf: 34–88 (% inhibition, *Escherichia coli*)	Tian, Liimatainen, et al. 2018

					spectrophotometer analysis	fruit: 13–89, leaf: 12–90 (% inhibition, *Staphylococcus aureus*)	
	Hippophaë rhamnoides cv. "Terhi," "Tytti"	Fruit leaf	70% ethanol containing 1.0% acetic acid	Total phenolics[a] phenolic acids[d] flavonoids[d] tannins[d]	Trypticase soya agar culture coupled with spectrophotometer analysis	100 mg/mL (10 μL–20 μL extract in 300 μL culture medium) fruit: −6 to 90, leaf: 94–100 (% inhibition, *Bacillus cereus*) fruit: 1–42, leaf: 24–55 (% inhibition, *Escherichia coli*) fruit: 6–92, leaf: 100–100 (% inhibition, *Listeria monocytogenes*) fruit: 33–98, leaf: 49–100 (% inhibition, *Salmonella enterica* sv. Typhimurium) fruit: 14–64, leaf: 99–100 (% inhibition, *Staphylococcus aureus*)	Tian, Puganen, et al. 2018
Strawberry	*Fragaria* × *ananassa* cv. "Albion," "Camarosa"	Fruit	Ethyl acetate	Total phenolics[a] phenolic acids[d] flavonols[d] tannins[d]	Agar diffusion assay, broth microdilution method	MIC: 650–700, MBC: 850–950 (μg/mL, *Listeria monocytogenes*) MIC: 600–660, MBC: 750–800 (μg/mL, *Salmonella* Typhimurium)	Vallejo et al. 2021
	Fragaria vesca	Leaf	80% ethanol	Total phenolics[a] total proanthocyanidins[b] total flavan-3-ols[e] phenolic acids[d] flavonoids[d]	Broth microdilution method	MIC: 3.3 (mg/mL, *Bacillus cereus*) MIC: 1.7 (mg/mL, *Campylobacter coli*) MIC: 3.3 (mg/mL, *Escherichia coli* O157:H7) MIC: 3.3 (mg/mL, *Listeria monocytogenes*) MIC: 3.3 (mg/mL, *Salmonella* Infantis) MIC: 1.2 (mg/mL, *Staphylococcus aureus*)	Mekinić et al. 2019
	Fragaria × *ananassa*	Fruit	Water	Total phenolics[a]	96-well microplate method, broth microdilution method	MIC: 2.5, MBC: 10 (%, wt/vol, *Acinetobacter baumanii*) MIC: 10, MBC: >10 (%, wt/vol, *Bacillus cereus*) MIC: 5, MBC: >10 (%, wt/vol, *Escherichia coli* O157:H7) MIC: 5, MBC: 10 (%, wt/vol, *Listeria monocytogenes*) MIC: 10, MBC: >10 (%, wt/vol, *Pseudomonas aeruginosa*) MIC: 5, MBC: >10 (%, wt/vol, *Salmonella* Typhimurium) MIC: 10, MBC: >10 (%, wt/vol, *Shigella* flexneri) MIC: 10, MBC: >10 (%, wt/vol, *Shigella* sonnei) MIC: 10, MBC: >10 (%, wt/vol, *Staphylococcus aureus*) MIC: 5, MBC: >10 (%, wt/vol, methicillin-resistant *Staphylococcus aureus*)	Khalifa et al. 2015

MIC, minimum inhibitory concentration; MBC, minimum bactericidal concentration; MTC, maximal tolerated concentration; GAE, gallic acid equivalence; CGE, cyanidin 3-*O*-glucoside equivalence.
[a]Total content of phenolics was measured by Folin–Ciocalteu assays;
[b]Total content of proanthocyanidins were determined by the vanillin-hydrochloricacid method;
[c]Total content of anthocyanins was measured by pH differential methods;
[d]Individual phenolic compounds were quantified by HPLC;
[e]Total content of flavan-3-ols/proanthocyanidins was quantified by 4-dimethlylaminocinnamaldehyde (DMAC) method;
[f]Total content of flavonoids was determined by aluminum complex;
[g]Total content of flavonoids were determined by colorimetric assay.

among all cultivars studied. Paunović et al. (2017) studied blackcurrant leaves of seven cultivars against *S. aureus*, *Klebsiella pneumoniae*, *E. coli*, *Proteus vulgaris*, *Proteus mirabilis*, and *B. subtilis*. After 24 h, leaf extracts of different cultivars exhibited varying inhibitory efficacy against each of bacteria strains. For example, cultivar "Titania" had the lowest MIC value of 156 μg/mL against *S. aureus*, which was over two-fold lower than that of "Ben Lomond" (359 μg/mL). In contrast, leaf extract of "Ben Lomond" was the most active (168 μg/mL) in suppressing the growth of *K. pneumoniae* strains, whereas "Titania" was the least (307). The impact of soil system was also revealed in this study. As shown in leaf extracts, treatment with bare fallow resulted in the highest anti-bacterial efficacy of leaf extract on all bacteria strains, and the lowest was found in those of currants covered with black plastic mulch. The authors did not provide valid explanation. Since the anti-bacterial efficacy in these treatment did not correlate with variation of phenolic content in leaf extract, phenolic compounds might not the only contributor to anti-bacterial activity. Moreover, ripening stages of berry plant and extracting solvents applied could also cause variation in inhibitory effect of berry species against *E. coli*, *L. monocytogenes*, *S. enterica* Typhimurium, and *S. aureus* (Deng et al. 2014).

Difference on cell structure of bacteria may also have an impact on the activities of berry extracts against pathogens. Compared to Gram-positive bacteria, Gram-negative microbes contain outer membrane. Acting as a permeability barrier, this hydrophilic surface is attributed to the lipopolysaccharide located in the outer leaflet of the membrane. However, previous studies have shown conflicting results when comparing the resistance of Gram-positive and Gram-negative microbes to extracts of berry species. Therefore, there is not sufficient research evidence to conclude whether plant-derived phenolic extracts are more active to Gram-positive or Gram-negative microbes, especially considering the large quantity of phenolics and their anti-bacterial mechanism being not fully determined (Bouarab-Chibane et al. 2019; Tian et al. 2018; Ilić et al. 2021).

For berry extracts, it is also often difficult to determine the major compounds responsible for various anti-bacterial effects, especially when low pH value also contributes to inhibition of bacteria growth. The accurate approach is to firstly isolate phenolic compounds from the crude extract and then to evaluate with target bacteria strains. Rodríguez-Pérez et al. (2016) investigated the contribution of major phenolics in cranberry juice in inhibiting uropathogenic *E. coli*. Twenty-five phenolic fractions were obtained from the extracts of cranberry juices by using semi-preparative HPLC. Phenolic profile of each fraction was determined by mass spectrometry before anti-bacterial assay with fourteen strains of *E. coli*. The results suggested that cranberry extract had a potent anti-*E. coli* activity with varying contribution by different phenolic components. Both myricetin aglycone and quercetin 3-*O*-rhamnoside effectively inhibited the biofilm formation of *E. coli*. Myricetin aglycone, quercetin 3-*O*-glucoside, A-type procyanidin dimer, and B-type prodelphinidin caused significant decrease in surface hydrophobicity of the bacteria. Statistical models have been applied to estimate the major contributing compounds to the anti-pathogenic effects of berry species extracts. Tian, Puganen, et al. (2018) used PLS and Pearson's correlation to establish correlation between concentrations of identified phenolics and growth inhibition of berry species extracts. Successful PLS model was built only on *S. aureus* and *B. cereus*. The total content of identified phenolics in extracts strongly correlated to the activities against these two bacteria. The major inhibitors included di- and tri-glycosylated isorhamnetins, and ellagitannins, as well as kaempferol 3-*O*-neohesperidoside, quercetin 3-*O*-(6-*O*-feruloylglucoside)-glucoside-7-*O*-rhamnoside, and quercetin 3-*O*-glucoside-7-*O*-rhamnoside. Moderate correlation was found with flavan-3-ols (primarily as catechins) and proanthocyanidins (dimers of B-type procyanidin). Yet, the derivatives of phenolic acids (hydroxycinnamic acids) were associated negatively with inhibitory effect. Pearson's correlation showed that the total content of identified phenolics correlated significantly with inhibition of *B. cereus*, *S. aureus*, *S. enterica* sv. Typhimurium, and *L. monocytogenes*. Compared to flavonoids, anti-*B. cereus* and anti-*S. aureus* capacities related more to the content of non-flavonoid phenolic compounds (mostly as phenolic acids and ellagitannins) in extracts. Within the group of flavonoids, proanthocyanidins (dimers and trimers of procyanidin) and glycosylated flavonols (quercetin) were strongly correlated with inhibition against *S. aureus* strains. Quercetin glycosides also appeared to be a strong inhibitor against *B. cereus* strain, suggested by the high correlation coefficient value. Again, statistical models provide only indication of the possible anti-bacterial contribution of phenolic compounds in extracts, which still needs further validation by anti-bacterial assay with purified phenolic compounds.

Structure-activity relationship of Nordic berry phenolics

Phenolic compounds are the main contributors to bioactivities of fruit and leaf extracts of Nordic berry species. Previous studies indicate that the bioactivities of phenolics and the mechanisms involved in the bioactivities are dependent on the molecular structures of these compounds. The structure-activity relationship (SAR) of the phenolic compounds has been investigated using *in vitro* assays; however, current research findings on SAR have been inconsistent and sometimes even conflicting among *in vitro* assays and different studies.

Anti-oxidative activities

Phenolic acids

Carboxylate group (–COOH) in phenyl ring undermines antioxidant capacity of phenolic acids due to its electron-withdrawing property interfering hydrogen donation. This negative influence can be compensated by 1) introduction of alkyl groups ($–CH_2–$) or ethylenic groups (–CH = CH–) between –COOH group and phenyl ring; and 2) esterification on –COOH group (Rice-Evans, Miller, and Paganga 1996). The former explains that both hydroxyphenylacetic

acids and hydroxycinnamic acids are generally more potent antioxidants than their benzoate counterparts (Table 4). Yet, the current findings in the literature comparing the anti-oxidative capacities between hydroxyphenylacetic and hydroxycinnamic acids are not consistent. The comparison between *o*-/*m*-/*p*-coumaric acid and *o*-/*m*-/*p*-hydroxyphenylacetic acid indicates that the mono-hydroxyl group in hydroxycinnamic acids seems to be a stronger hydrogen donor than that in hydroxyphenylacetic acids. In contrast, 3,4-dihydroxyphenylacetic acid shows better potency in quenching $ABTS^{\bullet+}$ than caffeic acid (3,4-dihydroxycinnamic acid) (Table 4). Enhancement of radicals scavenging is observed when caffeic acid esterified with quinic acid (Table 4). Esterification of –COOH with alkyl groups increases DPPH-quenching ability of both protocatechuic acid and caffeic acid, the enhancement of electron-donating is associated with the length of alkyl chain; however, it leads to a marked decrease on 3,4-dihydroxyphenylacetic acid (Reis et al. 2010; Silva et al. 2000).

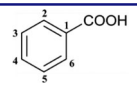
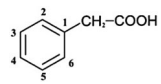
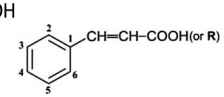
Within a specific group of phenolic acids, both number and orientation of hydroxyl groups (–OH) in the phenyl ring are the key determinants of anti-oxidative capacity; however, these effects on anti-oxidation may differ among different group of phenolic acids and various *in vitro* assays applied. As shown in Table 4, among hydroxybenzoic acids, the ability of scavenging both $ABTS^{\bullet+}$ and $DPPH^{\bullet}$ is enhanced with the increasing number of –OH group in the benzene ring. Gallic acid (3,4,5-trihydroxybenzoic acid) exerts the strongest radical-scavenging capacity, while most of dihydroxybenzoic acids have a medium $ABTS^{\bullet+}$ scavenging capacity. On the contrary, certain dihydroxybenzoic acids are inferior in quenching $DPPH^{\bullet}$ radicals. For example, there is no inhibition found from either 3,5- or 2,4-dihydroxybenzoic acids against $DPPH^{\bullet}$ radicals in some study. For monohydroxybenzoic acids, *m*-hydroxyl substitution results in higher ABTS values than the corresponding substitution at *p*- or *o*-position. Differing from hydroxybenzoic acids, *p*-coumaric acid presents higher activity against $ABTS^{\bullet+}$ (defined as TE, mM) than other monohydroxycinnamic acids, as well as dihydroxycinnamic acids; however, *p*-coumaric acid is confirmed to be ineffective in quenching $DPPH^{\bullet}$ (Table 4). In addition, introducing methoxy groups at *ortho*-position to –OH group increases the efficacy of 4-hydroxybenzoic acid against $DPPH^{\bullet}$, $ABTS^{\bullet+}$, $O_2^{\bullet-}$, and $OH^{\bullet}$, such as vanillic acid (4-OH and 3-OCH_3) and syringic acid (4-OH and 3,5-di OCH_3) comparing to *p*-hydroxybenzoic acid (4-OH) (Farhoosh et al. 2016; Zhou, Yin, and Yu 2006). Nevertheless, this does not apply to 4-hydroxycinnamic acid (*p*-coumaric acid). Piazzon et al. (2012) reported that anti-$ABTS^{\bullet+}$ ability decreased in the following order: ferulic acid (4-OH, 3-OCH_3) > *p*-coumaric acid (4-OH) > sinapic acid (4-OH, 3,5-di OCH_3). This study also showed that glycosylation at –OH groups led to a significantly reduction in antioxidant activity of phenolic acids.

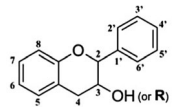
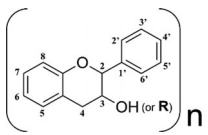
Flavonoids

The backbone of flavonoids (without a single hydroxyl group) is generally acknowledged as having no contribution to scavenging free radicals. Among flavonoids, strong anti-oxidative ability is observed commonly of the compounds having some or all of the following structural features: 1) an ortho-3′,4′-dihydroxyl group (catechol group) in the B ring; 2) a 3-OH group in the C ring; and 3) a 2,3-double bond coupled with a 4-oxo group in the C ring (Chen et al. 2018). Table 4 shows that quercetin, luteolin, and cyanidin were better $ABTS^{\bullet+}$ and $DPPH^{\bullet}$ scavengers than their 4′-monohydroxyl counterparts (such as kaempferol, apigenin, and pelargonidin, respectively). C_3-OH group in C ring increases the anti-oxidative activity of flavonoids by ensuring the whole molecule of flavonoids on a same plane, which permits electron delocalization and stabilization of flavonoid phenoxyl radicals. This is the reason why flavonols exceed flavones (with same structural features in A- and B-rings) as potent free-radical scavengers (Table 4). For C_2-C_3 double bond conjugated with the C_4-oxo group of C ring, as shown in Table 4, the efficacy of quercetin scavenging both $ABTS^{\bullet+}$ and $DPPH^{\bullet}$ is superior to that of catechin, suggesting the importance of this structural arrangement. It worthy of noticing, this positive effect may be dependent on the presence of both C_2-C_3 double bond and C_4-oxo group (Ferreira et al. 2015). The results from previous studies show some contradiction. Taxifolin (saturated C_2-C_3 bond and C_4-carbonyl group) exhibits lower anti-$ABTS^{\bullet+}$ but higher anti-$DPPH^{\bullet}$ potency than catechin. Similar findings have also been observed in comparison between naringenin and apigenin, as between taxifolin and quercetin (Table 4). Hydroxyl groups of A-ring are less important than the critical structure features described above; however, they still contribute to the increase in the total number of hydroxyl groups in molecules. The significance of A-ring –OH groups increases when –OH groups in B- and C-ring are occupied. Moreover, previous research showed that C_5-OH group coupled with C_3-OH and C_4-oxo groups provided an importance site of trapping metal cations, such as iron and copper (Procházková, Boušová, and Wilhelmová 2011).

Modification in these essential elements, such as methylation and glycosylation, influences the efficacy of flavonoids as antioxidants (Chen et al. 2018). Introducing a third hydroxy group in the B ring as in the case of 3′,4′,5′-trihydroxyl (pyrogallol) group, does not always strengthen radical-quenching ability compared to the catechol group. In Table 4, epigallocatechin and myricetin present stronger $ABTS^{\bullet+}$ quenching ability than epicatechin and quercetin, respectively, while the latter compounds have lower EC_{50}/IC_{50} defined as concentration causing 50% $DPPH^{\bullet}$ scavenged. Moreover, delphinidin and cyanidin have almost same TE value when measured by ABTS assay. This may have been due to the property of 3′,4′,5′-trihydroxyl moiety acting as both pro-oxidant and antioxidant. The flavonoid phenoxyl-radicals counteract the anti-oxidative effect by interacting with oxygen and producing quinones and superoxide anion instead of donating hydrogen atoms (Procházková, Boušová, and Wilhelmová 2011). Esterification at C_3-OH group with a gallic acid enhances the antioxidant capacity of flavan-3-ols (Table 4). The anti-$ABTS^{\bullet+}$ and anti-$DPPH^{\bullet}$ activities of flavan-3-ols are also

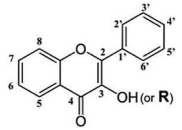
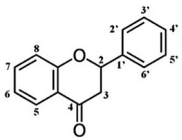
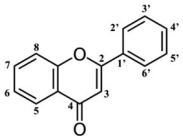
Table 4. Previous study on anti-oxidative capacity of some phenolic compounds measured ABTS and DPPH assays.

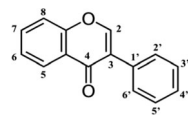
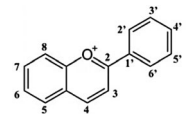
Compounds	Hydroxyl (OH) group substituents		Other substituents	Anti-oxidative capacity	
	No. of OH	OH position		ABTS	DPPH
					
Hydroxybenzoic acids					
o-Hydroxybenzoic acid (salicylic acid)	1	2-OH	—	0.04 ± 0.01^{a} 0.04 ± 0.00^{b}	0.05 ± 0.00^{b} 0 ± 0^{h}
m-Hydroxybenzoic acid	1	3-OH	—	0.84 ± 0.05^{a} 0.03 ± 0.00^{b}	0.07 ± 0.00^{b} 0 ± 0^{h}
p-Hydroxybenzoic acid	1	4-OH	—	0.08 ± 0.01^{a} 0.03 ± 0.00^{b} 0^{c}	0.06 ± 0.00^{b} 0^{d}
4-Hydroxy-3-methoxybenzoic acid (vanillic acid)	1	4-OH	3-OCH_3	1.43 ± 0.05^{a} 0.09 ± 0.00^{b} 1.12^{c} 2.1909^{i}	0.06 ± 0.00^{b}
4-Hydroxy-3,5-dimethoxybenzoic acid (syringic acid)	1	4-OH	3,5-OCH_3	1.36 ± 0.01^{a} 1.39 ± 0.02^{b} 1.2^{c} 4.1088^{i}	1.33 ± 0.01^{b} 63^{d} 12.3 ± 0.0^{e}
2,3-Dihydroxybenoic acid	2	2,3-OH	—	1.46 ± 0.01^{a}	46 ± 3^{h}
2,4-Dihydroxybenoic acid (β-resorcylic acid)	2	2,4-OH	—	1.22 ± 0.02^{b}	1.27 ± 0.01^{b} 0 ± 0^{h}
2,5-Dihydroxybenoic acid (gentisic acid)	2	2,5-OH	—	1.04 ± 0.03^{a}	7.6 ± 0.2^{e} 31 ± 0^{h}
3,4-Dihydroxybenoic acid (protocatechuic acid)	2	3,4-OH	—	1.19 ± 0.03^{a} 1.15 ± 0.01^{b}	1.29 ± 0.01^{b} 11.1 ± 0.0^{e} 15.0^{f} 2.2 ± 0.1^{g} 41 ± 1^{h}
3,5-Dihydroxybenoic acid (α-resorcylic acid)	2	3,5-OH	—	2.15 ± 0.05^{a}	1 ± 0^{h}
3,4,5-Trihydroxybenoic acid (gallic acid)	3	3,4,5-OH	—	3.01 ± 0.05^{a} 3.52 ± 0.03^{b} 7.354^{i}	3.92 ± 0.03^{b} 5.1 ± 0.1^{e} 12.0^{f} 75 ± 2^{h}
					
Hydroxyphenylacetic acids					
o-Hydroxyphenylacetic acid	1	2-OH	—	0.99 ± 0.09^{a}	
m-Hydroxyphenylacetic acid	1	3-OH	—	0.90 ± 0.11^{a}	
p-Hydroxyphenylacetic acid	1	4-OH	—	0.34 ± 0.10^{a} 1.2017^{i}	0 ± 0^{h}
4-Hydroxy-3-methoxyphenylacetic acid	1	4-OH	3-OCH_3	1.72 ± 0.06^{a}	0.84 ± 0.00^{b}
2,5-Dihydroxyphenylacetic acid	2	2,5-OH	—	0.91 ± 0.05^{a}	
3,4-Dihydroxyphenylacetic acid	2	3,4-OH	—	2.19 ± 0.08^{a}	71 ± 0^{h}
					
Hydroxycinnamic acids and derivatives					
2-Hydroxycinnamic acid (*o*-coumaric acid)	1	2-OH	—	0.99 ± 0.15^{a} 0.93 ± 0.01^{b} 2.2009^{i}	

3-Hydroxycinnamic acid (*m*-coumaric acid)	1	3-OH	—	1.21 ± 0.02[a] 0.82 ± 0.00[b]	0.75 ± 0.00[b]
3-Hydroxy-4-methoxycinnamic acid (isoferulic acid)	1	3-OH	4-OCH_3	1.53 ± 0.01[b]	1.24 ± 0.01[b]
4-Hydroxycinnamic acid (*p*-coumaric acid)	1	4-OH	—	2.22 ± 0.06[a] 1.96 ± 0.02[b] 1.5[c] 3.9137[i]	1.44 ± 0.01[b] 0[d] 255 ± 64[g]
4-Hydroxy-3-methoxycinnamic acid (ferulic acid)	1	4-OH	3-OCH_3	1.90 ± 0.02[a] 1.92 ± 0.02[b] 1.66[c] 4.3967[i]	1.49 ± 0.02[b] 40[d] 24.7 ± 0.4[e] 4.9 ± 0.1[g]
Ferulic acid 4-*O*-sulfate	0	—	3-OCH_3, 4-OSO_3H	0.3805[i]	
Ferulic acid 4-*O*-glucuronide	0	—	3-OCH_3, 4-*O*-glucuronide	0.0543[i]	
4-Hydroxy-3,5-dimethoxycinnamic acid (sinapic acid)	1	4-OH	3,5-OCH_3	3.7791[i]	4.5 ± 0.2[g]
2,4-Dihydroxycinnamic acid (umbellic acid)	2	2,4-OH	—		8.6 ± 0.1[g]
3,4-Dihydroxycinnamic acid (caffeic acid)	2	3,4-OH	—	1.26 ± 0.01[a] 1.31 ± 0.01[b] 2.4284[i]	1.24 ± 0.01[b] 12.1 ± 0.2[e] 2.6 ± 0.1[g] 44 ± 1[h]
5-*O*-caffeoylquinic acid (neochlorogenic acid)	2	4,5-OH	R = quinic acid group	1.56 ± 0.01[b]	1.75 ± 0.00[b]
3-*O*-caffeoylquinic acid (chlorogenic acid)	2	3,4-OH	R = quinic acid group	1.8891[i]	2.5 ± 0.1[g] 93 ± 4[h]
Caffeic acid 3-*O*-glucuronide	1	4-OH	3-*O*-glucuronide	2.2477[i]	
Caffeic acid 4-*O*-glucuronide	1	3-OH	4-*O*-glucuronide	0.7499[i]	
					
Flavan-3-ols					
Catechin	5	3, 5, 7, 3′, 4′	—	2.40 ± 0.05[a] 3.04 ± 0.03[b]	2.95 ± 0.04[b] 6.0 ± 0.2[e] 18.19 ± 0.93[j]
Epicatechin	5	3, 5, 7, 3′, 4′	—	2.50 ± 0.02[a] 3.08 ± 0.04[b]	3.18 ± 0.02[b] 4.5 ± 0.2[e] 16.09 ± 0.41[j]
Epigallocatechin	6	3, 5, 7, 3′, 4′, 5′	—	3.80 ± 0.06[a] 3.71 ± 0.02[b]	3.56 ± 0.02[b] 5.1 ± 0.1[e]
Catechin gallate	7	5, 7, 3′, 4′, three OH groups in R	R = galloyl group	5.25 ± 0.02[b]	5.56 ± 0.03[b]
Epicatechin gallate	7	5, 7, 3′, 4′, three OH groups in R	R = galloyl group	4.90 ± 0.02[a] 5.29 ± 0.03[b]	5.26 ± 0.02[b] 4.2 ± 0.1[e]
Epigallocatechin gallate	8	5, 7, 3′, 4′, 5′, three OH groups in R	R = galloyl group	4.80 ± 0.06[a] 5.95 ± 0.17[b]	6.09 ± 0.03[b] 3.6 ± 0.0[e]
					
Proanthocyanidins					
Procyanidin B-1 (dimer)	10 (n = 2)	3, 5, 7, 3′, 4′	—	6.14 ± 0.12[b]	5.94 ± 0.10[b] 3.2 ± 0.0[e]
Procyanidin B-2 (dimer)	10 (n = 2)	3, 5, 7, 3′, 4′	—		3.4 ± 0.4[e]
Procyanidin B-2 digallate (dimer)	14 (n = 2)	5, 7, 3′, 4′, three OH groups in R	R = galloyl group	9.18 ± 0.33[b]	8.79 ± 0.24[b]
Procyanidin C-1 (trimer)	15 (n = 3)	3, 5, 7, 3′, 4′		8.29 ± 0.25[b]	7.93 ± 0.35[b]

(*continued*)

Table 4. Continued.

Compounds	Hydroxyl (OH) group substituents		Other substituents	Anti-oxidative capacity	
	No. of OH	OH position		ABTS	DPPH
					
Flavonols					
Kaempferol	4	3, 5, 7, 4′	—	1.34 ± 0.08[a] 1.59 ± 0.02[b]	1.32 ± 0.01[b] 18.8 ± 0.0[e] 28.05 ± 0.28[j]
Kaempferol 3-*O*-glucoside	3	5, 7, 4′	3-*O*-glucoside	0.14 ± 0.02[b]	0.15 ± 0.01[b]
Quercetin	5	3, 5, 7, 3′, 4′	—	4.70 ± 0.1[a] 4.42 ± 0.08[b]	4.60 ± 0.02[b] 5.5 ± 0.0[e] 10.89 ± 0.03[j]
Quercetin 3-*O*-rutinoside	4	5, 7, 3′, 4′	3-*O*-rutinoside	2.40 ± 0.06[a] 2.02 ± 0.02[b]	2.33 ± 0.03[b] 5.3 ± 0.1[e] 9.40 ± 0.31[j]
Quercetin 3-*O*-galactoside	4	5, 7, 3′, 4′	3-*O*-galactoside		10.01 ± 0.00[j]
Quercetin 3-*O*-rhamnoside	4	5, 7, 3′, 4′	3-*O*-rhamnoside	2.18 ± 0.02[b]	2.57 ± 0.02[b]
Quercetin 3-*O*-glucoside-7-*O*-rhamnoside	3	5, 3′, 4′	3-*O*-glucoside, 7-*O*-rhamnoside	1.56 ± 0.03[b]	1.63 ± 0.03[b]
Myricetin	6	3, 5, 7, 3′, 4′, 5′	—	3.10 ± 0.30[a] 1.31 ± 0.01[b]	1.38 ± 0.01[b] 3.6 ± 0.1[e]
					
Flavanone					
Naringenin	3	5, 7, 4′	—	1.53 ± 0.05[a] 0.22 ± 0.00[b]	0.14 ± 0.00[b] >1000[j]
Naringenin 7-*O*-rutinoside	2	5, 4′	7-*O*-rutinoside	0.76 ± 0.05[a] 0.10 ± 0.00[b]	0.08 ± 0.00[b]
Hesperetin	3	5, 7, 3′	4′-OCH_3	1.37 ± 0.08[a] 0.40 ± 0.02[b]	0.27 ± 0.00[b] 236.63 ± 0.86[j]
Hesperetin 7-*O*-rutinoside	2	5, 3′	7-*O*-rutinoside, 4′-OCH_3	1.08 ± 0.04[a] 0.10 ± 0.00[b]	0.08 ± 0.00[b] 281.41 ± 2.62[j]
Taxifolin	5	3, 5, 7, 3′, 4′	—	1.90 ± 0.03[a]	9.27 ± 0.26[j]
					
Flavones					
Chrysin	2	5, 7	—	1.43 ± 0.07[a] 0.08 ± 0.00[b]	0.05 ± 0.00[b] 492.57 ± 23.94[j]
Apigenin	3	5, 7, 4′	—	1.45 ± 0.08[a] 0.09 ± 0.00[b]	0.04 ± 0.00[b] 463.40 ± 22.28[j]
Apigenin 8-*C*-glucoside	3	5, 7, 4′	8-glucoside	0.22 ± 0.00[b]	0.21 ± 0.00[b]
Apigenin 7-*O*-glucoside	2	5, 4′	7-*O*-glucoside	0.08 ± 0.00[b]	0.05 ± 0.00[b]
Luteolin	4	5, 7, 3′, 4′	—	2.10 ± 0.05[a] 2.18 ± 0.02[b]	2.24 ± 0.02[b] 11.04 ± 0.38[j]

Luteolin 7-*O*-glucoside	3	5, 3′, 4′	7-*O*-glucoside	1.47 ± 0.00[b]	1.39 ± 0.02[b] 28.17 ± 0.69[j]
Luteolin 4′-*O*-glucoside	3	5, 7, 3′	4′-*O*-glucoside	1.74 ± 0.09[a]	
Luteolin 3′,7-*O*-diglucoside	2	5, 4′	3′,7-*O*-diglucoside	0.79 ± 0.04[a]	
					
Isoflavones					
Genistein	3	5, 7, 4′	—	0.12 ± 0.00[b]	0.10 ± 0.00[b]
Genistein 7-*O*-glucoside	2	5, 4′	7-*O*-glucoside	0.08 ± 0.00[b]	0.03 ± 0.00[b]
Daidzein	2	7, 4′	—	0.10 ± 0.00[b]	0.03 ± 0.00[b]
Daidzein 7-*O*-glucoside	1	4′	7-*O*-glucoside	0.07 ± 0.00[b]	0.04 ± 0.00[b]
Glycitein	2	7, 4′	6-OCH_3	0.10 ± 0.00[b]	0.02 ± 0.00[b]
					
Anthocyanidins and anthocyanins					
Cyanidin	5	3, 5, 7, 3′, 4′		4.40 ± 0.12[a]	11.62 ± 0.11[j]
Cyanidin 3-*O*-rutinoside	4	5, 7, 3′, 4′	3-*O*-rutinoside	3.25 ± 0.1[a]	
Cyanidin 3-*O*-galactoside	4	5, 7, 3′, 4′	3-*O*-galactoside	2.90 ± 0.03[a]	
Delphinidin	6	3, 5, 7, 3′, 4′, 5′		4.44 ± 0.11[a]	
Pelargonidin	4	3, 5, 7, 4′	—	1.30 ± 0.1[a]	
Peonidin	4	3, 5, 7, 4′	3′-OCH_3	2.22 ± 0.2[a]	
Malvidin	4	3, 5, 7, 4′	3′,5′-OCH_3	2.06 ± 0.1[a]	
Malvidin 3-*O*-glucoside	3	5, 7, 4′	3-*O*-glucoside, 3′,5′-OCH_3	1.78 ± 0.02[a]	

[a]The results were defined as the concentration of Trolox solution with equivalent antioxidant potential to a 1 mM concentration of the compound (mM) (Rice-Evans, Miller, and Paganga 1996);
[b]The results were defined as the concentration of Trolox solution with equivalent antioxidant potential to a 1 mM concentration of the compound (mM), the reaction for scavenging DPPH• was carried out for 120 min (Cai et al. 2006);
[c]The results were expressed as mmole of Trolox equivalents per mmole of phenolic acid (mM) (Zhou, Yin, and Yu 2006);
[d]The DPPH radical scavenging activities of phenolics were expressed as inhibition of DPPH• (%) for 1 min (Zhou, Yin, and Yu 2006);
[e]The DPPH radical scavenging activities of phenolics were expressed as the concentration (10^{-6} M) of the compound to give a 50% of DPPH• scavenging activities (EC_{50}) (Villaño et al. 2007);
[f]The DPPH radical scavenging activities of phenolics were expressed as the concentration (10^{-6} M) of the compound to give a 50% of DPPH• scavenging activities (EC_{50}) (Reis et al. 2010);
[g]The DPPH radical scavenging activities of phenolics were expressed as the concentration (10^{-5} M) of the compound to give a 50% of DPPH• scavenging activities (EC_{50}) (Terpinc and Abramovič 2010);
[h]The DPPH radical scavenging activities of phenolics were expressed as Inhibition of DPPH• (%) for 1 min (Sroka and Cisowski 2003);
[i]The results were expressed as the slope of dose-activity curve (Piazzon et al. 2012);
[j]The DPPH radical scavenging activities of phenolics were expressed as the concentration (10^{-6} M) of the compound to give a 50% inhibition of DPPH• (IC_{50}) (Seyoum, Asres, and El-Fiky 2006).

increased by esterification at C_4 with phloroglucinol. It is due to the fact that flavan-3-ols having saturated heterocyclic structure lacks electron delocalization between A- and B-ring. Thus, the increasing number of hydroxyl group is mainly responsible for the radical quenching activities of these flavan-3-ol derivatives. Nevertheless, it is noticed that esterification at C_3-OH or C_4 of flavan-3-ols has a negative impact on chelating metal ions (Zhang et al. 2015). For flavonols, (iso)flavones, anthocyanidins and anthocyanins containing an unsaturated C ring, the anti-$ABTS^{\bullet+}$ and anti-$DPPH^{\bullet}$ activities are reduced by blocking C_3-OH group via glycosylation (Table 4). Yet, there has not been clear pattern reported about the impact of the nature of sugar moiety on the anti-oxidative activities of flavonoid glycosides.

Tannins

Proanthocyanidins, as polymeric flavan-3-ols, generally follow the common patterns of SAR of flavonoids. Free 3′,4′-catechol group and 3-OH group of the monomeric units are indicators of high anti-oxidative potential. Different from monomeric flavonoids, the degree of polymerization influences the anti-oxidative activity of proanthocyanidins; however, no clear SAR relationship has been established between polymerization degree and radical-scavenging ability, which may depend on the nature of free radicals. The linkage between monomers may have an impact on the anti-oxidative capacity of proanthocyaninds. As shown in Table 4, B-type procyanidin trimers (procyanidin C1) present stronger capacity against $ABTS^{\bullet+}$ and $DPPH^{\bullet}$ radicals than its dimers and monomers. This is likely due to the abundance of the three critical structural elements mentioned above. The linkage of C_4-C_8 ensures producing of stable proanthocyanidins radicals during radical-scavenging process. However, in the study of Oldoni et al. (2016), procyanidin A1 and A2 (dimer) isolated from peanut skin showed significantly lower activities in ABTS and FRAP assays than their monomers. Ether bond between C_2 and C_7-OH may be responsible for the low anti-oxidative efficacy. The study also suggested that stereochemistry at C_3-OH group contributed to anti-oxidative activity of proanthocyanidins, due to a large deviation between the anti-oxidative activities of these two compounds. Ellagitannins act as anti-oxidative agents by both chelating metal cations and scavenging free radicals. In a research of Fe^{2+} ions-induced anti-$OH^{\bullet}$ assay, Moilanen et al. (2016) proposed that ellagitannins tended to form Fe^{2+}-ellagitannin complexes instead of directly scavenging $OH^{\bullet}$. Among structural features of ellagitannins, galloyl group was a more important contributor to scavenging of $DPPH^{\bullet}$ and $OH^{\bullet}$ compared to HHDP, DHHDP, and chebuloyl groups. It was also noticed that the abundance of hydroxyl groups results in a strong pro-oxidative effect, even when ellagitannins are present at low concentrations. This may explain some contradictory results from other antioxidant assays. Moreover, Kaneshima et al. (2016) studied six *C*-glycosidic ellagitannins isolated from seeds and peels of *Myrciaria dubia*. The abilities of the tannins quenching $ABTS^{\bullet+}$ and $DPPH^{\bullet}$ depended on the conformation of C_1-OH group of *D*-glucose, but ORAC results could not be explained by this structural feature.

Anti-bacterial activities

Phenolic acids

Aside from providing acidic environment, the anti-pathogenic potency of phenolic acids is ascribed to 1) alkyl side chain and 2) hydroxyl groups in phenol ring. Hydroxycinnamic acids exhibit higher efficacy than hydroxybenzoic acids that contain same number of –OH group when inhibiting growth of *B. subtilis*, *E. coli*, *Lactobacillus plantarum*, and *Lactobacillus hammesii* (Sánchez-Maldonado 2014). This may have been due to the fact that phenolic acids with unsaturated side chain had low polarity, which benefits diffusion across cell membrane, leading to acidified cytoplasm, and further death of cells. Esterification on alkyl side chain enhances the ability of hydroxycinnamic acids inhibiting both Gram-positive and Gram-negative strains. Andrade et al. (2015) compared the anti-bacterial activities of caffeic acid and its alkyl esters against *S. aureus* and *E. coli*. The results showed that the alkyl esters were more effective than caffeic acid due to the changes on hydrophobicity. *S. aureus* strain was susceptible to the esters with long alkyl side chains, whereas *E. coli* was more sensitive to the ones with medium length alkyl side chain. Hydroxyl groups in phenol ring weaken the ability of phenolic acids inhibiting bacterial strains, although this negative effect can be compensated via methylation at –OH groups. According to MIC values against *B. subtilis*, *E. coli*, *L. plantarum*, and *L. hammesii* strains, Sánchez-Maldonado, Schieber, and Gänzle (2011) ranked the anti-pathogenic capacity of benzoic acid and its hydroxyl derivatives in a decreasing order of: benzoic acid > *p*-hydroxybenzoic acid > protocatechuic acid > gallic acid. Syringic acid (4-OH; 3,5-OCH_3) had stronger inhibitory effect than gallic acid, which was still weaker than that of monohydroxybenzoic acids. Regarding hydroxycinnamic acids, the impact of –OH groups was minor, and methoxyl substitution at benzene ring showed no influence on anti-bacterial activity.

Flavonoids

The relationship between structure and anti-bacterial activity of flavonoids has not been fully determined yet, mainly due to different bacteria strains and various anti-bacterial mechanisms involved (Górniak, Bartoszewski, and Króliczewski 2019). In general, flavonoids preforming potent anti-bacterial efficacy highly relies on proper amphipathic character, which means both hydrophilic and hydrophobic structural features are required for inhibition of bacterial growth. The main structural impacts have been well-summarized in the recent articles (Farhadi et al. 2019; Makarewicz et al. 2021). Briefly, the degree of hydroxylation is proportional to the anti-bacterial ability of flavonols and flavones, especially at C_5 and C_7 of A-ring and $C_{3'}$, $C_{4'}$, and $C_{5'}$ of B-ring. In C-ring, a saturated C_2-C_3 bond enhances inhibitory effect of flavonoids against bacteria. A free C_3-OH group is essential

to flavonoids suppressing the growth of *E. coli*, methylation of which results in a decrease on the inhibitory potency. The impact of glycosylation on antibacterial activity varies among bacteria strains and flavonoid class; the sites of glycosylation and the length of sugar moieties may also play a role. Additionally, certain hydrophobic substituents in flavonoids, such as prenyl groups, alkylamino chains, alkyl chains, and nitrogen or oxygen containing heterocyclic moieties, also commonly contribute to enhancement of anti-bacterial capacity (Xie et al. 2015).

Tannins

Little is known about the influence of molecule structures on the anti-bacterial activity of tannins. Engels et al. (2011) proposed that the anti-bacterial activity of gallotannins relied on the affinity to iron, resulting in the inactivation of membrane-bound proteins. Thus, structural arrangements (such as introducing galloyl groups) may enhance the inhibition against foodborne pathogens via increasing the iron-binding capacity of tannins. Puljula et al. (2020) confirmed free galloyl group was essential for anti-bacterial capacity of ellagitannins after evaluation of twenty-two ellagitannins with *Clostridiales perfringens*, *E. coli*, *L. plantarum* and *S. aureus* strains. Yet, the effect of galloyl group was dependent on the bacteria species. The inhibitory effects of the ellagitannins against *E. coli* and *C. perfringens* were enhanced with the increasing number of free galloyl group, whereas no clear pattern was observed on *S. aureus*. Polymerization of tannins may also influence activities against certain bacterial strains. The study of Puljula et al. (2020) suggested that *E. coli* and *C. perfringens* strains were more sensitive to oligomeric ellagitannins than their monomers. On the contrary, the increase in the degree of polymerization may diminish the anti-bacterial activity of proanthocyanidins. Wang, Hsu, et al. (2015) reported that procyanidin dimers (including both A- and B-type) exceeded their trimers on growth inhibition of *S. aureus*. Moreover, in the same study, difference in the type of linkage between monomeric units of procyanidins led to variation of inhibitory effect. A-type procyanidin dimer showed a medium activity against *L. monocytogenes* and *B. cereus*, but B-type dimer had no effect on these two strains.

Application of Nordic berry species as food preservation

Current studies on Nordic berry species applied in food preservation

Due to the marked anti-oxidative and anti-bacterial activities in *in vitro* assays, Nordic berry species are considered as potential new food preservatives. So far, only a few berry species (blueberry, blackcurrant, cranberry, and cloudberry) has been studied at laboratory-scale in meat products as reviewed previously (Ahmad et al. 2015; Lorenzo et al. 2018; Efenberger-Szmechtyk, Nowak, and Czyzowska 2021). In these previous studies, except few cases where whole berries are added directly into meat materials (Muzolf-Panek et al. 2016), most of the berry samples are extracted with absolute aqueous methanol or ethanol. The organic components are later evaporated; the residuals are re-dissolved in water and then added into poultry or pork products. Previous studies focus mainly on berry species retarding oxidation of sensitive ingredients. Lipid and protein oxidation in meat products are evaluated with thiobarbituric acid reagent substances (TBARS) and 2,4-dinitrophenylhydrazine (DNPH) assays, respectively. Oxidation-induced volatile compounds (mainly as aldehydes) are analyzed in certain studies using gas chromatography/mass spectrometry (GC/MS) as part of the anti-oxidative evaluation. Extracts of certain berry species also influence texture and discoloration during storage. Yet, the potential of berry species in inhibiting microbial spoilage has been seldom investigated in meat matrix.

Briefly, the previous research showed that the addition of blueberry, blackcurrant, cranberry, and cloudberry (0.1–30 g/kg meat) effectively delayed oxidation of lipid and protein in raw or cooked meat products during a 0–4 °C storage of 6–14 days. Addition of extract of blackcurrant (2% of final product, wt/wt) also enhanced the redness (higher a* value determined by color meter) and darkness (lower L* value) of pork patties during 9-day storage (4 °C). This is likely due to abundance of anthocyanins in blackcurrant, providing meat samples a dark color. It remains unclear whether the compounds in berry extracts inhibit the oxidation of ferrous heme-iron (Fe^{2+}) into its ferric form (Fe^{3+}), thus delay discoloration of meat (Jia et al. 2012). In contrast, adding 2% of blueberry puffing caused a significant reduction of redness of pork meatloaf (Muzolf-Panek et al. 2016). Since blueberry is also rich in anthocyanins, the contradictory result may be related to the presenting form of berry species in meat matrix. For other Nordic berry species, ethanolic extract of hawthorn (*C. monogyna*) fruits was added in pork patties (3% of dose, wt/wt) to investigate the potential impact on the level of lipid and protein oxidation during chilled (2 °C, 12 days) storage (Ganhão et al. 2013; Ganhão, Morcuende, and Estévez 2010). Over the whole studied period, the treated samples showed remarkably lower TBARS and DNPH values than the control, indicating the role of extracts of hawthorn in protecting lipid and protein from oxidation. Impact of hawthorn extracts was also observed on texture of pork patties. Using texture analyzer, cooked patties treated with hawthorn exhibited significant higher values of hardness and chewiness after 12 days storage. No effect of hawthorn extract was shown on color deterioration of samples. This may be attributed to that anthocyanins are present in hawthorn at low level and these temperature-sensitive compounds degraded during cooking process (170 °C for 18 min). Moreover, some colored products may also form from Maillard reactions during heating. Inferior anti-bacterial efficacies of lingonberry and sea buckthorn were reported in the observation of Alakomi et al. (2017). Acidified ethanolic extracts (70% aqueous ethanol and 1% acetic acid) of these two berries were added into marinated broiler chicken cuts for 13-day storage at 6 °C. Sea buckhorn and lingonberry extracts (both at 2 g/kg of

meat products) did not show significant antimicrobial effect against the spoilage microbes studied (*Brochothrix thermosphacta*, *Enterobacteriaceae*, lactic acid bacteria, and psychrotrophic bacteria), which might have been due to the low dosage of the extracts applied.

Application of berry species in meat products is also dependent on acceptance from customers. Haugaard et al. (2014) investigated the impact of addition of berry extracts as preservatives on customers' preference of meat production. Twenty-one participants showed a generally positive attitude toward utilization of berries as new meat preservation approach. Their concerns focused on the quality of final food products rather than preservation technology, especially on taste, appearance, texture, and shelf life. In this study, participants were given a list of berry species as potential preservatives. Cranberry and lingonberry were highly accepted by the participants. Most of the participants were positive toward using redcurrant, blueberry, and chokeberry in meat products. On the contrary, the participants' opinions on application of sea buckthorn were mostly negative. It may be related to the concern that the compounds contributing to the sourness and bitterness of sea buckthorn may influence the taste of meat products (Ma et al. 2021). The study by Haugaard et al. (2014) also suggested that the form of berry materials appearing in meat products influenced the consumers' acceptance. The consumers preferred that berry materials should be invisible (such as juices or purée) instead of being visible (chopped or whole berries). When evaluating the sausages with addition of juice and frozen fruits of blueberry, the participants chose products added with juice over those with whole berries, since the purple/blue liquid leaking out of berries into surrounding meat made the products unappealing. For addition of juices, the colors of the sausages with different dosages (20–80 g/kg of sausages) of blueberry juice were acceptable; however, the dose of 120 g/kg offered a gray tone, insinuating the spoilage of products. In addition, a general opinion was that the meat products should match the color of the added berry. For example, juices of blueberry were preferred to add into a beef sausage rather than pork sausage, since dark color of blueberries fitted beef better than pork.

Aside from fruits of berry species, certain by-products from berry cultivation and juice-pressing industry have been recently investigated to prolong storage of meat products. Nowak et al. (2016) studied polyphenolic extracts from leaves of sour cherry and blackcurrant, as well as their possibility as natural antioxidant and antimicrobial agents in pork sausages. According to the TBARS values, both leaf extracts strongly reduced lipid oxidation in samples during 28 days of storage (4 °C), but were still inferior to nitrates. Microbiological results showed that the leaf extracts were effective against strains of lactic acid bacteria, *Pseudomonas*, *B. thermosphacta*, and *Enterobacteriaceae* in 14 days of refrigerated storage. A trained panel of 10 individuals evaluated the sensorial properties (taste, color, and odor) of sausage samples. It suggested that the addition of studied leaf extracts did not provide any negative impacts on the sensory attributes of pork sausages, but neither of them could enhance the characteristic red color of meat products as nitrates. Mäkinen et al. (2020) extracted bilberry leaf and sea buckthorn leaf using subcritical water extraction (SWE) process. SWE leaf extracts of bilberry and sea buckthorn as well as their dried leaf powders were applied in pork sausage and marinated chicken leg slices during 20- and 8-day storage, respectively, at 6 °C. Compared to the treatment with a mixture of sodium nitrite and ascorbic acid, the addition of bilberry leaf powders (2%, wt/wt) and its SWE extract (0.2%, wt/wt) prevented lipid oxidation significantly in sausages determined by TBARS. Nevertheless, sensory evaluation on overall preference, color, and flavor suggested that samples with either of these additions were found least appealing. All the samples added with leaf materials had significantly lower levels of TBARS than the sample prepared with only basic marinade. The overall preference of chicken slices marinated with both 0.4% and 4% SWE extract of bilberry leaf, and 4% extract of sea buckthorn leaf were closed to that of the samples using basic marinade only.

For pomaces of Nordic berry species, the water and ethanol extracts of defatted cranberry pomaces (2% of dose) effectively inhibited the growth of food pathogenic bacteria strains (such as *L. monocytogenes*, *B. thermosphacta*, *P. putida*, and aerobic mesophilic bacteria) in pork slurry, burger patties, and cooked ham during storage of 16, 16, and 40 days (4–5 °C), respectively. As the dominant phenolic compounds in the extracts, anthocyanins (mainly glycosylated cyanidins and peonidins) might be responsible for the protective effect. The extracts showed slight impacts on pH and metmyoglobin content of meat products but not on water activity. The addition of the pomace extracts resulted in some color changes, but no negative effect was observed on sensory quality of burger patties and cooked ham (Tamkutė et al. 2019). Damerau et al. (2020) added dry powders of two juice-pressing residues (lingonberry and sea buckthorn, 3% of dose, wt/wt) separately into Baltic herring (*Clupea harengus membras*) fish mince to study their impact on lipid oxidation during frozen storage. Major components of both residues were determined, such as carotenoids, tocopherols, tocotrienols, and phenolics. The level of lipid oxidation of fish samples was determined by peroxide value (PV) and contents of individual fatty acids measured with GC. Compared to control group (with fish mince only) and the group treated with ethylenediaminetetraacetic acid calcium disodium salt (EDTA), ascorbic acid, and α-tocopherol, fish mince mixed with berry residues showed the significantly lowest loss of eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) after ten-month of frozen storage. PV value, however, was increased in all samples during the storage period. Authors assumed that it might be caused by other oxidative species in the samples, since PV was based on an indirect measurement of hydroperoxides. The sensory test of all studied fish mince was conducted. Over 150 participants tasted fish loaves prepared from tested fish mince, egg, toast crumb, heavy cream, and salt. The samples treated with berry materials received an average rating between "dislike slightly" and "neither like nor dislike".

Current status and future prospects of Nordic berry species using as food preservation

Some Nordic berry species have been reported to effectively protect lipids and proteins of meat products from oxidation during storage. These laboratory-scaled studies have revealed the potential of berry materials as food preservative. Generally, in the most of previous research, berry species are studied as crude extracts. The chemical composition of which is not determined, or only certain groups of phytochemicals are quantified at total contents. This limited compositional information makes it impossible to compare protecting function of various extracts of berry species in meat products, or to determine the major contributing compounds. Moreover, the anti-oxidative activities on lipids and proteins are evaluated at general levels mostly by colorimetric methods. Thus, it is still unclear how the plant materials protect specific food components.

A systematic sensory evaluation of berry species-treated food products is also commonly missing from previous studies. In some studies, the impact of extracts from berry species on color and texture of chill stored meat products has been evaluated by monitoring changes in compositional parameter measured by instrumental analyses, but the changes in these parameters often do not give any information on approval of the products by consumers. It is necessary to perform sensory evaluation since some chemicals in berry species may result in changes in sensory quality of meat products. The correlation of chemicals present in berry species to orosensory properties of food products has been investigated in the matrix of juices. The contents of sugars and organic acids contribute to sweetness and sourness. Astringency is associated with some phenolic compounds, such as glycosylated flavonols, hydroxycinnamic acids, and procyanidins (Laaksonen et al. 2013; Laaksonen et al. 2015). This may explain the findings in those studies including sensory tests, where the dosage of berry species extracts having the most effective preservation often results in unpleasant changes on appearance, odor, or flavor of final products.

So far, no valid results have shown that the berry species exceed commonly used synthetic preservatives against lipid and protein oxidation. This is due to that the comparison between berry species/corresponding extracts and synthetic counterparts is conducted only in few studies, and the results suggest that higher amount of the crude extracts of berry species may be required in order to achieve similar protective effects as that obtained with synthetic preservatives. For example, Jia et al. (2012) compared the efficacy of blackcurrant extract (extracted by 40% ethanol) with BHA against lipid and protein oxidation in raw pork patties during storage at 4 °C. To decrease the contents of TBARS and carbonyl group at similar level in the studied meat material, addition of blackcurrant extracts at dosage of 10 and 20 g/kg meat was needed, in comparison with only 0.2 g/kg of BHA. The authors determined the total content of anthocyanin in the extracts by pH differential method, but it was still unlikely to explain the low efficacy of blackcurrant extracts due to lack of information of other chemicals.

Application of raw extracts of berry species as food preservatives may be challenging. As discussed in previous chapters, the crude extract of berry species is complex of phytochemicals. Many factors (biological, environmental, and industrial) can cause deviation of phenolic composition of berry species, and further influence their anti-oxidative and anti-bacterial activities. The constantly changing phenolic profiles in plant materials will not only present challenges for determination of the dosage of addition, but also may lead to changes in the sensory property of final products which eventually reduce costumer's acceptance. In addition, cautions should be taken when applying side-streams of berry species as potential food preservatives. Certain leaf extracts are rich in aromatic compounds, such as prunasin in leaves of chokeberry and saskatoon, and tyramine in leaves of red- and whitecurrant (Tian et al. 2017). The extracts as such should be fully evaluated from food safety point view before considered as potential food preservatives. Therefore, the raw extract is not ideal option from the side of food industry.

For the future research, it is more rational to fractionate raw extracts to obtain isolates, which have targeted and simplified chemical profiles and exhibit high anti-oxidative and anti-bacterial efficacy, with minimal impact on sensory quality of food products. This requires a precise determination of the major components contributing to the bioactivities of berry species extracts. From concern of food safety, a systematically evaluation to phenolic isolates is necessary, as well as their stability during processing and storage. Regarding sensitive nutrients, more studies are urgently needed, focusing on the responses of specific ingredients to the addition of phenolic isolates, such as various fatty acids, peptides, and amino acids. Modern metabolomics and chemometrics approaches offer powerful tools, which should be applied in research to understand the compositional change during food storage and the impact of food preservation technologies.

Summary

Nordic berry species are good sources of phenolic compounds. Due to potent anti-oxidative and anti-bacterial activities shown in different *in vitro* assays, the extracts of fruits and even side-streams of berry production and processing (leaves and pomaces) showed potent capacities on protecting the quality of some food products during storage, all suggesting the potential of developing natural food preservatives from these materials. Despite the promising results obtained by the studies carried out so far, further activities in research development is needed in order to develop food preservatives from berry species for industrial use. Besides challenges brought by impact on sensory quality of food products, a low protective efficacy compared to synthetic preservatives, is often associated with the complex and unstable phenolic composition in crude extracts. Further, it is still challenging to determine main contributor of bioactivities among a large number of components of the extracts. Future investigation should focus on pinpointing and

fractionating main contributing phenolics responsible for anti-oxidation and anti-bacteria in food products. It also needs to emphasize mechanism of phenolics protecting specific nutrients and impact of the phenolic additives on orosensory of final products. To achieve the commercial application of Nordic berry species as food preservatives, it is necessary for food industry to establish a low-cost approach to obtain the phenolic fractions of high protective efficacy. The targeted food products should also be selected carefully according to costumers' acceptance. From the point of view of circular economy, it is critical and urgent to effectively utilize leaves and pomaces of berry species. However, exploitation of leaves and pomaces still needs thorough knowledge of the composition not only of phenolic compounds but also of other phytochemicals in extracts, considering some of these compounds may cause food safety issues. Application of state-of-art metabolomics approach would enable comprehensive profiling of the secondary metabolites present in the by-products of berry species, which will considerably enhance the understanding of the food safety aspects related to these materials.

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Disclosure statement

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References

Abeywickrama, G., S. C. Debnath, P. Ambigaipalan, and F. Shahidi. 2016. Phenolics of selected cranberry genotypes (*Vaccinium macrocarpon* Ait.) and their antioxidant efficacy. *Journal of Agricultural and Food Chemistry* 64 (49):9342–51. doi: 10.1021/acs.jafc.6b04291.

Ahmad, S. R., P. Gokulakrishnan, R. Giriprasad, and M. A. Yatoo. 2015. Fruit-based natural antioxidants in meat and meat products: A review. *Critical Reviews in Food Science and Nutrition* 55 (11): 1503–13. doi: 10.1080/10408398.2012.701674.

Alakomi, H. L., J. Maukonen, K. Honkapaa, E. Storgards, K. W. Quirin, B. Yang, and M. Saarela. 2017. Effect of plant antimicrobial agents containing marinades on storage stability and microbiological quality of broiler chicken cuts packed with modified atmosphere packaging. *Journal of Food Protection* 80 (10):1689–96. doi: 10.4315/0362-028X.JFP-17-076.

Albuquerque, B. R., S. A. Heleno, M. B. P. P. Oliveira, L. Barros, and I. C. F. R. Ferreira. 2021. Phenolic compounds: Current industrial applications, limitations and future challenges. *Food & Function* 12 (1):14–29. doi: 10.1039/d0fo02324h.

Andrade, M., S. Benfeito, P. Soares, D. Magalhães e Silva, J. Loureiro, A. Borges, F. Borges, and M. Simões. 2015. Fine-tuning of the hydrophobicity of caffeic acid: Studies on the antimicrobial activity against *Staphylococcus aureus* and *Escherichia coli*. *RSC Advances* 5 (66):53915–25. doi: 10.1039/C5RA05840F.

Arend, G. D., W. T. Adorno, K. Rezzadori, M. D. Luccio, V. C. Chaves, F. H. Reginatto, and J. C. C. Petrus. 2017. Concentration of phenolic compounds from strawberry (*Fragaria* × *ananassa* Duch) juice by nanofiltration membrane. *Journal of Food Engineering* 201: 36–41. doi: 10.1016/j.jfoodeng.2017.01.014.

Aziz, M., and S. Karboune. 2018. Natural antimicrobial/antioxidant agents in meat and poultry products as well as fruits and vegetables: A review. *Critical Reviews in Food Science and Nutrition* 58 (3): 486–511. doi: 10.1080/10408398.2016.1194256.

Bartkiene, E., V. Lele, V. Sakiene, P. Zavistanaviciute, M. Ruzauskas, J. Bernatoniene, V. Jakstas, P. Viskelis, D. Zadeike, and G. Juodeikiene. 2019. Improvement of the antimicrobial activity of lactic acid bacteria in combination with berries/fruits and dairy industry by-products. *Journal of the Science of Food and Agriculture* 99 (8):3992–4002. doi: 10.1002/jsfa.9625.

Bolling, B. W., R. Taheri, R. Pei, S. Kranz, M. Yu, S. N. Durocher, and M. H. Brand. 2015. Harvest date affects aronia juice polyphenols, sugars, and antioxidant activity, but not anthocyanin stability. *Food Chemistry* 187:189–96. doi: 10.1016/j.foodchem.2015.04.106.

Bouarab-Chibane, L., V. Forquet, P. Lantéri, Y. Clément, L. Léonard-Akkari, N. Oulahal, P. Degraeve, and C. Bordes. 2019. Antibacterial properties of polyphenols: Characterization and QSAR (Quantitative structure-activity relationship) models. *Frontiers in Microbiology* 10: 829. doi: 10.3389/fmicb.2019.00829.

Bujor, O. C., C. L. Bourvellec, I. Volf, V. I. Popa, and C. Dufour. 2016. Seasonal variations of the phenolic constituents in bilberry (*Vaccinium myrtillus* L.) leaves, stems and fruits, and their antioxidant activity. *Food Chemistry* 213:58–68. doi: 10.1016/j.foodchem.2016.06.042.

Bujor, O. C., C. Ginies, V. I. Popa, and C. Dufour. 2018. Phenolic compounds and antioxidant activity of lingonberry (*Vaccinium vitis-idaea* L.) leaf, stem and fruit at different harvest periods. *Food Chemistry* 252:356–65. doi: 10.1016/j.foodchem.2018.01.052.

Bustos, M. C., D. Rocha-Parra, I. Sampedro, S. De Pascual-Teresa, and A. E. León. 2018. The influence of different air-drying conditions on bioactive compounds and antioxidant Activity of berries. *Journal of Agricultural and Food Chemistry* 66 (11):2714–23. doi: 10.1021/acs.jafc.7b05395.

Cai, Y. Z., M. Sun, J. Xing, Q. Luo, and H. Corke. 2006. Structure-radical scavenging activity relationships of phenolic compounds from traditional Chinese medicinal plants. *Life Sciences* 78 (25):2872–88. doi: 10.1016/j.lfs.2005.11.004.

Chen, L., H. Teng, Z. Xie, H. Cao, W. S. Cheang, K. Skalicka-Woniak, M. I. Georgiev, and J. Xiao. 2018. Modifications of dietary flavonoids towards improved bioactivity: An update on structure-activity relationship. *Critical Reviews in Food Science and Nutrition* 58 (4): 513–27. doi: 10.1080/10408398.2016.1196334.

Colak, N., A. K. Primetta, K. R. Riihinen, L. Jaakola, J. Grúz, M. Strnad, H. Torun, and F. A. Ayaz. 2017. Phenolic compounds and antioxidant capacity in different-colored and non-pigmented berries of bilberry (*Vaccinium myrtillus* L.). *Food Bioscience* 20:67–78. doi: 10.1016/j.fbio.2017.06.004.

Criste, A., A. C. Urcan, A. Bunea, F. R. P. Furtuna, N. K. Olah, R. H. Madden, and N. Corcionivoschi. 2020. Phytochemical composition and biological activity of berries and leaves from four Romanian sea buckthorn (*Hippophae rhamnoides* L.) varieties. *Molecules* 25 (5): 1170. doi: 10.3390/molecules25051170.

Damerau, A., T. Kakko, Y. Tian, S. Tuomasjukka, M. Sandell, A. Hopia, and B. Yang. 2020. Effect of supercritical CO_2 plant extract and berry press cakes on stability and consumer acceptance of frozen Baltic herring (*Clupea harengus membras*) mince. *Food Chemistry* 332:127385. doi: 10.1016/j.foodchem.2020.127385.

Das, Q., M. R. Islam, M. F. Marcone, K. Warriner, and M. S. Diarra. 2017. Potential of berry extracts to control foodborne pathogens. *Food Control* 73:650–62. doi: 10.1016/j.foodcont.2016.09.019.

Deng, Y., G. Yang, J. Yue, B. Qian, Z. Liu, D. Wang, Y. Zhong, and Y. Zhao. 2014. Influences of ripening stages and extracting solvents on the polyphenolic compounds, antimicrobial and antioxidant

activities of blueberry leaf extracts. *Food Control* 38 (1):184–91. doi: 10.1016/j.foodcont.2013.10.023.

de Souza, D. R., J. L. Willems, and N. H. Low. 2019. Phenolic composition and antioxidant activities of saskatoon berry fruit and pomace. *Food Chemistry* 290:168–77. doi: 10.1016/j.foodchem.2019.03.077.

de Souza, V. R., P. A. P. Pereira, T. L. T. da Silva, L. C. de Oliveira Lima, R. Pio, and F. Queiroz. 2014. Determination of the bioactive compounds, antioxidant activity and chemical composition of Brazilian blackberry, red raspberry, strawberry, blueberry and sweet cherry fruits. *Food Chemistry* 156:362–8. doi: 10.1016/j.foodchem.2014.01.125.

Dienaitė, L., A. Pukalskas, M. Pukalskienė, C. V. Pereira, A. A. Matias, and P. R. Venskutonis. 2020. Phytochemical composition, antioxidant and antiproliferative activities of defatted sea buckthorn (*Hippophaë rhamnoides* L.) berry pomace fractions consecutively recovered by pressurized ethanol and water. *Antioxidants* 9 (4):274. doi: 10.3390/antiox9040274.

Dudonné, S., P. Dubé, F. F. Anhê, G. Pilon, A. Marette, M. Lemire, C. Harris, E. Dewailly, and Y. Desjardins. 2015. Comprehensive analysis of phenolic compounds and abscisic acid profiles of twelve native Canadian berries. *Journal of Food Composition and Analysis* 44:214–24. doi: 10.1016/j.jfca.2015.09.003.

Efenberger-Szmechtyk, M., A. Nowak, and A. Czyzowska. 2021. Plant extracts rich in polyphenols: Antibacterial agents and natural preservatives for meat and meat products. *Critical Reviews in Food Science and Nutrition* 61 (1):149–78. doi: 10.1080/10408398.2020.1722060.

Engels, C., A. Schieber, and M. G. Gänzle. 2011. Inhibitory spectra and modes of antimicrobial action of gallotannins from mango kernels (*Mangifera indica* L.). *Applied and Environmental Microbiology* 77 (7):2215–23. doi: 10.1128/AEM.02521-10.

Farhadi, F., B. Khameneh, M. Iranshahi, and M. Iranshahy. 2019. Antibacterial activity of flavonoids and their structure-activity relationship: An update review. *Phytotherapy Research: PTR* 33 (1):13–40. doi: 10.1002/ptr.6208.

Farhoosh, R., S. Johnny, M. Asnaashari, N. Molaahmadibahraseman, and A. Sharif. 2016. Structure-antioxidant activity relationships of *o*-hydroxyl, *o*-methoxy, and alkyl ester derivatives of *p*-hydroxybenzoic acid. *Food Chemistry* 194:128–34. doi: 10.1016/j.foodchem.2015.08.003.

Ferreira, R. D. Q., S. J. Greco, M. Delarmelina, and K. C. Weber. 2015. Electrochemical quantification of the structure/antioxidant activity relationship of flavonoids. *Electrochimica Acta* 163:161–6. doi: 10.1016/j.electacta.2015.02.164.

Fraisse, D., A. Bred, C. Felgines, and F. Senejoux. 2020. Screening and characterization of antiglycoxidant anthocyanins from *Vaccinium myrtillus* fruit using DPPH and methylglyoxal pre-column HPLC assays. *Antioxidants* 9 (6)1–11.512. doi: 10.3390/antiox9060:.

Ganhão, R., M. Estévez, M. Armenteros, and D. Morcuende. 2013. Mediterranean berries as inhibitors of lipid oxidation in porcine burger patties subjected to cooking and chilled storage. *Journal of Integrative Agriculture* 12 (11):1982–92. doi: 10.1016/S2095-3119(13)60636-X.

Ganhão, R., D. Morcuende, and M. Estévez. 2010. Protein oxidation in emulsified cooked burger patties with added fruit extracts: Influence on colour and texture deterioration during chill storage. *Meat Science* 85 (3):402–9. doi: 10.1016/j.meatsci.2010.02.008.

Górniak, I., R. Bartoszewski, and J. Króliczewski. 2019. Comprehensive review of antimicrobial activities of plant flavonoids. *Phytochemistry Reviews* 18 (1):241–72. doi: 10.1007/s11101-018-9591-z.

Guo, R., X. Chang, X. Guo, C. S. Brennan, T. Li, X. Fu, and R. H. Liu. 2017. Phenolic compounds, antioxidant activity, antiproliferative activity and bioaccessibility of Sea buckthorn (*Hippophaë rhamnoides* L.) berries as affected by *in vitro* digestion. *Food & Function* 8 (11):4229–40. doi: 10.1039/c7fo00917h.

Guo, R., X. Guo, T. Li, X. Fu, and R. H. Liu. 2017. Comparative assessment of phytochemical profiles, antioxidant and antiproliferative activities of Sea buckthorn (*Hippophaë rhamnoides* L.) berries. *Food Chemistry* 221:997–1003. doi: 10.1016/j.foodchem.2016.11.063.

Haugaard, P., F. Hansen, M. Jensen, and K. G. Grunert. 2014. Consumer attitudes toward new technique for preserving organic meat using herbs and berries. *Meat Science* 96 (1):126–35. doi: 10.1016/j.meatsci.2013.06.010.

Ilić, D. P., D. Z. Troter, L. P. Stanojević, J. B. Zvezdanović, D. D. Vukotić, and V. D. Nikolić. 2021. Cranberry (*Vaccinium macrocarpon* L.) fruit juice from Serbia: UHPLC-DAD-MS/MS characterization, antibacterial and antioxidant activities. *LWT - Food Science and Technology* 146:111399. doi: 10.1016/j.lwt.2021.111399.

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.

Kaneshima, T., T. Myoda, M. Nakata, T. Fujimori, K. Toeda, and M. Nishizawa. 2016. Antioxidant activity of C-glycosidic ellagitannins from the seeds and peel of camu-camu (*Myrciaria dubia*). *LWT - Food Science and Technology* 69:76–81. doi: 10.1016/j.lwt.2016.01.024.

Karlińska, E., A. Masny, M. Cieślak, J. Macierzyński, Ł. Pecio, A. Stochmal, and M. Kosmala. 2021. Ellagitannins in roots, leaves, and fruits of strawberry (*Fragaria* × *ananassa* Duch.) vary with developmental stage and cultivar. *Scientia Horticulturae* 275:109665. doi: 10.1016/j.scienta.2020.109665.

Khalifa, H. O., M. Kamimoto, T. Shimamoto, and T. Shimamoto. 2015. Antimicrobial effects of blueberry, raspberry, and strawberry aqueous extracts and their effects on virulence gene expression in *Vibrio cholerae*. *Phytotherapy Research: PTR* 29 (11):1791–7. doi: 10.1002/ptr.5436.

Klewicka, E., M. Sójka, R. Klewicki, K. Kołodziejczyk, L. Lipińska, and A. Nowak. 2016. Ellagitannins from raspberry (*Rubus idaeus* L.) fruit as natural inhibitors of *Geotrichum candidum*. *Molecules* 21 (7):908. doi: 10.3390/molecules21070908.

Laaksonen, O., L. Mäkilä, R. Tahvonen, H. Kallio, and B. Yang. 2013. Sensory quality and compositional characteristics of blackcurrant juices produced by different processes. *Food Chemistry* 138 (4):2421–9. doi: 10.1016/j.foodchem.2012.12.035.

Laaksonen, O., J.-P. Salminen, L. Mäkilä, H. P. Kallio, and B. Yang. 2015. Proanthocyanidins and their contribution to sensory attributes of black currant juices. *Journal of Agricultural and Food Chemistry* 63 (22):5373–80. doi: 10.1021/acs.jafc.5b01287.

Lachowicz, S., J. Oszmiański, and S. Pluta. 2017. The composition of bioactive compounds and antioxidant activity of Saskatoon berry (*Amelanchier alnifolia* Nutt.) genotypes grown in central Poland. *Food Chemistry* 235:234–43. doi: 10.1016/j.foodchem.2017.05.050.

Lorenzo, J. M., M. Pateiro, R. Domínguez, F. J. Barba, P. Putnik, D. B. Kovačević, A. Shpigelman, D. Granato, and D. Franco. 2018. Berries extracts as natural antioxidants in meat products: A review. *Food Research International (Ottawa, Ont.)* 106:1095–104. doi: 10.1016/j.foodres.2017.12.005.

Ma, X., J. Moilanen, O. Laaksonen, W. Yang, E. Tenhu, and B. Yang. 2019. Phenolic compounds and antioxidant activities of tea-type infusions processed from sea buckthorn (*Hippophaë rhamnoides*) leaves. *Food Chemistry* 272:1–11. doi: 10.1016/j.foodchem.2018.08.006.

Ma, X., W. Yang, H. Kallio, and B. Yang. 2021. Health promoting properties and sensory characteristics of phytochemicals in berries and leaves of sea buckthorn (*Hippophaë rhamnoides*). *Critical Reviews in Food Science and Nutrition*. doi: 10.1080/10408398.2020.1869921.

Makarewicz, M., I. Drożdż, T. Tarko, and A. Duda-Chodak. 2021. The interactions between polyphenols and microorganisms, especially gut microbiota. *Antioxidants* 10 (2):188–70. doi: 10.3390/antiox10020188.

Mäkinen, S., J. Hellström, M. Mäki, R. Korpinen, and P. H. Mattila. 2020. Bilberry and sea buckthorn leaves and their subcritical water extracts prevent lipid oxidation in meat products. *Foods* 9 (3):265. doi: 10.3390/foods9030265.

Mekinić, I. G., D. Skroza, I. Ljubenkov, V. Katalinić, and V. Šimat. 2019. Antioxidant and antimicrobial potential of phenolic metabolites from traditionally used Mediterranean herbs and spices. *Foods* 8 (11):579. doi: 10.3390/foods8110579.

Mikulic-Petkovsek, M., A. Slatnar, F. Stampar, and R. Veberic. 2012. HPLC-MS^n identification and quantification of flavonol glycosides in 28 wild and cultivated berry species. *Food Chemistry* 135 (4): 2138–46. doi: 10.1016/j.foodchem.2012.06.115.

Moilanen, J., M. Karonen, P. Tähtinen, R. Jacquet, S. Quideau, and J. P. Salminen. 2016. Biological activity of ellagitannins: Effects as anti-oxidants, pro-oxidants and metal chelators. *Phytochemistry* 125: 65–72. doi: 10.1016/j.phytochem.2016.02.008.

Moilanen, J., P. Koskinen, and J. P. Salminen. 2015. Distribution and content of ellagitannins in finnish plant species. *Phytochemistry* 116 (1):188–97. doi: 10.1016/j.phytochem.2015.03.002.

Muzolf-Panek, M., A. Waśkiewicz, R. Kowalski, and P. Konieczny. 2016. The Effect of blueberries on the oxidative stability of pork meatloaf during chilled storage. *Journal of Food Processing and Preservation* 40 (5):899–909. doi: 10.1111/jfpp.12668.

Nile, S. H., and S. W. Park. 2014. Edible berries: Bioactive components and their effect on human health. *Nutrition (Burbank, Los Angeles County, Calif.)* 30 (2):134–44. doi: 10.1016/j.nut.2013.04.007.

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.

Oldoni, T. L. C., P. S. Melo, A. P. Massarioli, I. A. M. Moreno, R. M. N. Bezerra, P. L. Rosalen, G. V. J. Da Silva, A. M. Nascimento, and S. M. Alencar. 2016. Bioassay-guided isolation of proanthocyanidins with antioxidant activity from peanut (*Arachis hypogaea*) skin by combination of chromatography techniques. *Food Chemistry* 192:306–12. doi: 10.1016/j.foodchem.2015.07.004.

Oroian, M., and I. Escriche. 2015. Antioxidants: Characterization, natural sources, extraction and analysis. *Food Research International (Ottawa, Ont.)* 74:10–36. doi: 10.1016/j.foodres.2015.04.018.

Oszmiański, J., A. Wojdyło, S. Lachowicz, J. Gorzelany, and N. Matłok. 2016. Comparison of bioactive potential of cranberry fruit and fruit-based products versus leaves. *Journal of Functional Foods* 22:232–42. doi: 10.1016/j.jff.2016.01.015.

Paunović, S. M., P. Mašković, M. Nikolić, and R. Miletić. 2017. Bioactive compounds and antimicrobial activity of black currant (*Ribes nigrum* L.) berries and leaves extract obtained by different soil management system. *Scientia Horticulturae* 222:69–75. doi: 10.1016/j.scienta.2017.05.015.

Piazzon, A., U. Vrhovsek, D. Masuero, F. Mattivi, F. Mandoj, and M. Nardini. 2012. Antioxidant activity of phenolic acids and their metabolites: Synthesis and antioxidant properties of the sulfate derivatives of ferulic and caffeic acids and of the acyl glucuronide of ferulic acid. *Journal of Agricultural and Food Chemistry* 60 (50): 12312–23. doi: 10.1021/jf304076z.

Procházková, D., I. Boušová, and N. Wilhelmová. 2011. Antioxidant and prooxidant properties of flavonoids. *Fitoterapia* 82 (4):513–23. doi: 10.1016/j.fitote.2011.01.018.

Puganen, A., H. P. Kallio, K. M. Schaich, J. P. Suomela, and B. Yang. 2018. Red/green currant and sea buckthorn berry press residues as potential sources of antioxidants for food use. *Journal of Agricultural and Food Chemistry* 66 (13):3426–34. doi: 10.1021/acs.jafc.8b00177.

Puljula, E., G. Walton, M. J. Woodward, and M. Karonen. 2020. Antimicrobial activities of ellagitannins against *Clostridiales perfringens*, *Escherichia coli*, *Lactobacillus plantarum* and *Staphylococcus aureus*. *Molecules* 25 (16):3714. doi: 10.3390/molecules25163714.

Puupponen-Pimiä, R., L. Nohynek, H. L. Alakomi, and K. M. Oksman-Caldentey. 2005. Bioactive berry compounds - Novel tools against human pathogens. *Applied Microbiology and Biotechnology* 67 (1): 8–18. doi: 10.1007/s00253-004-1817-x.

Raudone, L., G. Vilkickyte, L. Pitkauskaite, R. Raudonis, R. Vainoriene, and V. Motiekaityte. 2019. Antioxidant activities of *Vaccinium vitis-idaea* L. leaves within cultivars and their phenolic compounds. *Molecules* 24 (5):844. doi: 10.3390/molecules24050844.

Reis, B., M. Martins, B. Barreto, N. Milhazes, E. M. Garrido, P. Silva, J. Garrido, and F. Borges. 2010. Structure-property-activity relationship of phenolic acids and derivatives. Protocatechuic acid alkyl esters. *Journal of Agricultural and Food Chemistry* 58 (11):6986–93. doi: 10.1021/jf100569j.

Rice-Evans, C. A., N. J. Miller, and G. Paganga. 1996. Structure-antioxidant activity relationships of flavonoids and phenolic acids. *Free Radical Biology & Medicine* 20 (7):933–56. doi: 10.1016/0891-5849(95)02227-9.

Rocha, R., J. Pinela, R. M. V. Abreu, M. Añibarro-Ortega, T. C. S. P. Pires, A. L. Saldanha, M. J. Alves, A. Nogueira, I. C. F. R. Ferreira, and L. Barros. 2020. Extraction of anthocyanins from red raspberry for natural food colorants development: Processes optimization and in vitro bioactivity. *Processes* 8 (11):1447–19. doi: 10.3390/pr8111447.

Rodríguez-Pérez, C., R. Quirantes-Piné, J. Uberos, C. Jiménez-Sánchez, A. Peña, and A. Segura-Carretero. 2016. Antibacterial activity of isolated phenolic compounds from cranberry (*Vaccinium macrocarpon*) against *Escherichia coli*. *Food & Function* 7 (3):1564–73. doi: 10.1039/C5FO01441G.

Salaheen, S., E. Jaiswal, J. Joo, M. Peng, R. Ho, D. OConnor, K. Adlerz, J. H. Aranda-Espinoza, and D. Biswas. 2016. Bioactive extracts from berry byproducts on the pathogenicity of *Salmonella Typhimurium*. *International Journal of Food Microbiology* 237:128–35. doi: 10.1016/j.ijfoodmicro.2016.08.027.

Samoticha, J., A. Wojdyło, and K. Lech. 2016. The influence of different the drying methods on chemical composition and antioxidant activity in chokeberries. *LWT - Food Science and Technology* 66: 484–9. doi: 10.1016/j.lwt.2015.10.073.

Sánchez-Maldonado, A. F. 2014. Mode of action, interaction and recovery of plant secondary metabolites for potential applications as food preservatives. PhD diss., University of Alberta, Canada.

Sánchez-Maldonado, A. F., A. Schieber, and M. G. Gänzle. 2011. Structure-function relationships of the antibacterial activity of phenolic acids and their metabolism by lactic acid bacteria. *Journal of Applied Microbiology* 111 (5):1176–84. doi: 10.1111/j.1365-2672.2011.05141.x.

Seyoum, A., K. Asres, and F. K. El-Fiky. 2006. Structure-radical scavenging activity relationships of flavonoids. *Phytochemistry* 67 (18): 2058–70. doi: 10.1016/j.phytochem.2006.07.002.

Shah, M. A., S. J. D. Bosco, and S. A. Mir. 2014. Plant extracts as natural antioxidants in meat and meat products. *Meat Science* 98 (1): 21–33. doi: 10.1016/j.meatsci.2014.03.020.

Shen, X., X. Sun, Q. Xie, H. Liu, Y. Zhao, Y. Pan, C. A. Hwang, and V. C. H. Wu. 2014. Antimicrobial effect of blueberry (*Vaccinium corymbosum* L.) extracts against the growth of *Listeria monocytogenes* and *Salmonella Enteritidis*. *Food Control* 35 (1):159–65. doi: 10.1016/j.foodcont.2013.06.040.

Silva, F. A. M., F. Borges, C. Guimarães, J. L. F. C. Lima, C. Matos, and S. Reis. 2000. Phenolic Acids and Derivatives: Studies on the Relationship among Structure, Radical Scavenging Activity, and Physicochemical Parameters †. *Journal of Agricultural and Food Chemistry* 48 (6):2122–6. doi:10.1021/jf9913110.

Silva, P., S. Ferreira, and F. M. Nunes. 2017. Elderberry (*Sambucus nigra* L.) by-products a source of anthocyanins and antioxidant polyphenols. *Industrial Crops and Products* 95:227–34. doi: 10.1016/j.indcrop.2016.10.018.

Silva, S., E. M. Costa, M. R. Costa, M. F. Pereira, J. O. Pereira, J. C. Soares, and M. M. Pintado. 2015. Aqueous extracts of *Vaccinium corymbosum* as inhibitors of *Staphylococcus aureus*. *Food Control* 51: 314–20. doi: 10.1016/j.foodcont.2014.11.040.

Sroka, Z., and W. Cisowski. 2003. Hydrogen peroxide scavenging, antioxidant and anti-radical activity of some phenolic acids. *Food and Chemical Toxicology* 41 (6):753–8. doi: 10.1016/S0278-6915(02)00329-0.

Ștefănescu, B. E., L. F. Călinoiu, F. Ranga, F. Fetea, A. Mocan, D. C. Vodnar, and G. Crișan. 2020. Chemical composition and biological activities of the nord-west romanian wild bilberry (*Vaccinium myrtillus* L.) and lingonberry (*Vaccinium vitis-idaea* L.) leaves. *Antioxidants* 9 (6):495. doi: 10.3390/antiox9060495.

Suvanto, J., P. Tähtinen, S. Valkamaa, M. T. Engström, M. Karonen, and J. P. Salminen. 2018. Variability in foliar ellagitannins of *Hippophaë rhamnoides* L. and identification of a new ellagitannin,

Hippophaenin C. *Journal of Agricultural and Food Chemistry* 66 (3): 613–20. doi: 10.1021/acs.jafc.7b04834.

Sytařová, I., J. Orsavová, L. Snopek, J. Mlček, Ł. Byczyński, and L. Mišurcová. 2020. Impact of phenolic compounds and vitamins C and E on antioxidant activity of sea buckthorn (*Hippophaë rhamnoides* L.) berries and leaves of diverse ripening times. *Food Chemistry* 310:125784. doi: 10.1016/j.foodchem.2019.125784.

Tamkutė, L., B. M. Gil, J. R. Carballido, M. Pukalskienė, and P. R. Venskutonis. 2019. Effect of cranberry pomace extracts isolated by pressurized ethanol and water on the inhibition of food pathogenic/spoilage bacteria and the quality of pork products. *Food Research International (Ottawa, Ont.)* 120:38–51. doi: 10.1016/j.foodres.2019.02.025.

Terpinc, P., and H. Abramovič. 2010. A kinetic approach for evaluation of the antioxidant activity of selected phenolic acids. *Food Chemistry* 121 (2):366–71. doi: 10.1016/j.foodchem.2009.12.037.

Tian, Y., O. Laaksonen, H. Haikonen, A. Vanag, H. Ejaz, K. Linderborg, S. Karhu, and B. Yang. 2019. Compositional diversity among blackcurrant (*Ribes nigrum*) cultivars originating from European countries. *Journal of Agricultural and Food Chemistry* 67 (19):5621–33. doi: 10.1021/acs.jafc.9b00033.

Tian, Y., J. Liimatainen, A. L. Alanne, A. Lindstedt, P. Liu, J. Sinkkonen, H. Kallio, and B. Yang. 2017. Phenolic compounds extracted by acidic aqueous ethanol from berries and leaves of different berry plants. *Food Chemistry* 220:266–81. doi: 10.1016/j.foodchem.2016.09.145.

Tian, Y., J. Liimatainen, A. Puganen, H. L. Alakomi, J. Sinkkonen, and B. Yang. 2018. Sephadex LH-20 fractionation and bioactivities of phenolic compounds from extracts of Finnish berry plants. *Food Research International (Ottawa, Ont.)* 113:115–30. doi: 10.1016/j.foodres.2018.06.041.

Tian, Y., A. Puganen, H. L. Alakomi, A. Uusitupa, M. Saarela, and B. Yang. 2018. Antioxidative and antibacterial activities of aqueous ethanol extracts of berries, leaves, and branches of berry plants. *Food Research International (Ottawa, Ont.)* 106:291–303. doi: 10.1016/j.foodres.2017.12.071.

Vagiri, M., S. Conner, D. Stewart, S. C. Andersson, S. Verrall, E. Johansson, and K. Rumpunen. 2015. Phenolic compounds in blackcurrant (*Ribes nigrum* L.) leaves relative to leaf position and harvest date. *Food Chemistry* 172:135–42. doi: 10.1016/j.foodchem.2014.09.041.

Vallejo, C. V., C. J. Minahk, G. C. Rollán, and M. J. Rodríguez-Vaquero. 2021. Inactivation of *Listeria monocytogenes* and *Salmonella Typhimurium* in strawberry juice enriched with strawberry polyphenols. *Journal of the Science of Food and Agriculture* 101 (2):441–8. doi: 10.1002/jsfa.10653.

Veberic, R., A. Slatnar, J. Bizjak, F. Stampar, and M. Mikulic-Petkovsek. 2015. Anthocyanin composition of different wild and cultivated berry species. *LWT - Food Science and Technology* 60 (1): 509–17. doi: 10.1016/j.lwt.2014.08.033.

Villaño, D., M. S. Fernández-Pachón, M. L. Moyá, A. M. Troncoso, and M. C. García-Parrilla. 2007. Radical scavenging ability of polyphenolic compounds towards DPPH free radical. *Talanta* 71 (1):230–5. doi: 10.1016/j.talanta.2006.03.050.

Wang, C. M., Y. M. Hsu, Y. L. Jhan, S. J. Tsai, S. X. Lin, C. H. Su, and C. H. Chou. 2015. Structure elucidation of procyanidins isolated from *Rhododendron formosanum* and their anti-oxidative and anti-bacterial activities. *Molecules (Basel, Switzerland)* 20 (7):12787–803. doi: 10.3390/molecules200712787.

Wang, L. J., J. Wu, H. X. Wang, S. S. Li, X. C. Zheng, H. Du, Y. J. Xu, and L. S. Wang. 2015. Composition of phenolic compounds and antioxidant activity in the leaves of blueberry cultivars. *Journal of Functional Foods* 16:295–304. doi: 10.1016/j.jff.2015.04.027.

Wen, L., X. Guo, R. H. Liu, L. You, A. M. Abbasi, and X. Fu. 2015. Phenolic contents and cellular antioxidant activity of Chinese hawthorn "*crataegus pinnatifida*". *Food Chemistry* 186:54–62. doi: 10.1016/j.foodchem.2015.03.017.

Wu, H., Z. Chai, R. P. Hutabarat, Q. Zeng, L. Niu, D. Li, H. Yu, and W. Huang. 2019. Blueberry leaves from 73 different cultivars in southeastern China as nutraceutical supplements rich in antioxidants. *Food Research International (Ottawa, Ont.)* 122:548–60. doi: 10.1016/j.foodres.2019.05.015.

Xie, Y., W. Yang, F. Tang, X. Chen, and L. Ren. 2015. Antibacterial activities of flavonoids: Structure-activity relationship and mechanism. *Current Medicinal Chemistry* 22 (1):132–49. doi: 10.2174/0929867321666140916113443.

Yang, B., and M. Kortesniemi. 2015. Clinical evidence on potential health benefits of berries. *Current Opinion in Food Science* 2:36–42. doi: 10.1016/j.cofs.2015.01.002.

Yang, W., O. Laaksonen, H. Kallio, and B. Yang. 2016. Proanthocyanidins in sea buckthorn (*Hippophaë rhamnoides* L.) berries of different origins with special reference to the influence of genetic background and growth location. *Journal of Agricultural and Food Chemistry* 64 (6):1274–82. doi: 10.1021/acs.jafc.5b05718.

Yang, W., X. Ma, O. Laaksonen, W. He, H. Kallio, and B. Yang. 2019. Effects of latitude and weather conditions on proanthocyanidins in blackcurrant (*Ribes nigrum*) of Finnish commercial cultivars. *Journal of Agricultural and Food Chemistry* 67 (51):14038–47. doi: 10.1021/acs.jafc.9b06031.

Zhang, S., Y. Cui, L. Li, Y. Li, P. Zhou, L. Luo, and B. Sun. 2015. Preparative HSCCC isolation of phloroglucinolysis products from grape seed polymeric proanthocyanidins as new powerful antioxidants. *Food Chemistry* 188:422–9. doi: 10.1016/j.foodchem.2015.05.030.

Zhao, M., J. Bai, X. Bu, Y. Tang, W. Han, D. Li, L. Wang, Y. Yang, and Y. Xu. 2021. Microwave-assisted aqueous two-phase extraction of phenolic compounds from *Ribes nigrum* L. and its antibacterial effect on foodborne pathogens. *Food Control* 119:107449. doi: 10.1016/j.foodcont.2020.107449.

Zhou, K., J. J. Yin, and L. Yu. 2006. ESR determination of the reactions between selected phenolic acids and free radicals or transition metals. *Food Chemistry* 95 (3):446–57. doi: 10.1016/j.foodchem.2005.01.026.