Blackcurrants (*Ribes nigrum*): A Review on Chemistry, Processing, and Health Benefits

Regina E. Cortez and Elvira Gonzalez de Mejia

Abstract: Blackcurrants (BC; *Ribes nigrum*) are relatively new to the U.S. market; however, they are well known and popular in Europe and Asia. The use of BC has been trending worldwide, particularly in the United States. We believe that demand for BC will grow as consumers become aware of the several potential health benefits these berries offer. The objectives of this review were to provide an up-to-date summary of information on BC based on articles published within the last decade; furthermore, to provide the food industry insights into possibilities for the utilization of BC. The chemistry, processing methods, and health benefits have been highlighted in addition to how the environment and variety impact the chemical constituents of BC. A search for journal publications on BC was conducted, which included keywords such as chemical characterization, health benefits, processing, technologies, anthocyanins (ANC), and proanthocyanidins. This review provides up-to-date information available on the subject. In conclusion, BC and their products have industrial uses from which extractions can be made to produce natural pigments to be used as food additives. BC contain flavonoids, specifically ANC, which provide the fruits with their purple color. BC are a rich source of phytochemicals with potent antioxidant, antimicrobial, and anti-inflammatory properties. Also, BC have the potential to improve overall human health particularly with diseases associated with inflammation and regulation of blood glucose.

Keywords: anthocyanins, anti-inflammation, antioxidant, berry processing, blackcurrants (*Ribes nigrum*)

Introduction

Blackcurrants (BC; *Ribes nigrum*) are small dark purple fruits that come from medium-sized woody shrubs (Figure 1) (Corrigan, Hedderley, Langford, & Zou, 2014; Törrönen et al., 2012). These shrubs are native to colder climate areas such as northern Europe, northern Asia, and central Asia, with Poland being the primary exporter (80% to 90% of global exports) of fresh and processed BC (Michalska, Wojdyło, Łysiak, Lech, & Figiel, 2017). Table 1 offers details about BC producing countries. Production of BC depends on the genetics of each cultivar and the temperature of the growing environment. BC are well known in European markets but not in the United States. BC have remained relatively unknown to the U.S. market because they were prohibited from being grown in the United States from the early 20th century until the 1980s. This was due to significant losses by the lumber industry, which discovered that some native and non-native species of the *Ribes* genus could act as vectors for the fungus *Cronartium ribicola*. This is the cause of the white pine blister rust, disease in pine trees, which leads to mortality of native five-needle pines, important for the U.S. lumber industry (Tanguay, Cox, Munck, Weimer, & Villani, 2015). Since then, new cultivars have been produced that do not act as vectors for the fungus, in addition to the already resistant BC cultivar "Consort." Currently, some U.S. farmers have a renewed interest in this high-value crop because BC and BC products are trending worldwide. In fact, the Intl. Blackcurrant Assn. (IBA), which began in 2008 in Christchurch, New Zealand, now has associations with growing programs in Denmark, France, Germany, Japan, Netherlands, Norway, Poland, Ukraine, and the United Kingdom (Table 1). Additionally, there is also the Blackcurrant Foundation, which is based in the United Kingdom. Other BC breeding programs can also be found in countries such as the United States, Finland, Poland, Canada, New Zealand (Institute for Plant and Food Research), the United Kingdom (James Hutton Institute, Scotland), Ukraine, Sweden, Estonia, Latvia, Lithuania, Romania, Russia, and Serbia. Table 2 presents examples of sources for BC berries. It was reported in 2017 that 3,100 new BC products appeared globally, 199 of which were from the United States alone (FONA International, 2017; Figure 2). It should also be noted that the IBA has its own New Product Development Unit, which promotes the development of BC products (International Blackcurrant Association, 2016). BC, which are known for their characteristic deep shades of purple, also have a characteristic bitter and astringent flavor. This is why it is quite common to find BC products with significant amounts of sugar added. BC are also known to have a high concentration of flavonoids, specifically anthocyanins (ANC), which provide the fruits with their purple color (Archaina, Leiva, Salvatori, & Schebor, 2018). These winter hardy berries are a rich source of phytochemicals that are potent antioxidants, antimicrobials, and have anti-inflammatory properties (Nour, Stampar, Veberic, & Jakopic, 2013). The objective of this review was to summarize and offer up-to-date information of the available literature regarding BC and their chemical, sensorial, processing, and potential biological properties.

Chemistry and Sensory Properties of BC

BC (*R. nigrum*) are widely recognized for containing high levels of polyphenols, specifically ANC (Figure 3) and proanthocyanidins (PAC; Figure 4), when compared with other berries (Lee et al., 2015). Both blackberries and blueberries have lower total ANC concentrations compared to BC (949.4 ± 4.0, 1,562.2 ± 52.4, and 1,741 ± 48.8 mg/100 g, dry weight (DW), respectively; Lee et al., 2015). Interestingly, a large degree of variability of ANC concentrations was demonstrated among three BC cultivars ("Record," "Blackdown," and "Ronix")

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[Correction added on September 3, 2019 after first online publication: the reference was deleted.]

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Figure 1–Blackcurrant (*Ribes nigrum*) berries and plants grown in Champaign County, Illinois. Blackcurrant farmers in Champaign, IL standing next to a young blackcurrant bush for size perspective; a close-up photo of how blackcurrant berries grow in groups; and a young blackcurrant bush growing in Champaign, IL. There has been a recent increase in the number of blackcurrant farms in Illinois in the past 5 years. Permission for pictures has been granted.

Table 1–World blackcurrant production information.

World producer	Production tonnage	Hectares of land	Reference
Denmark	3,000	500	www.blackcurrant-iba.com/blackcurrants-denmark/
France	4,600	1,300	www.blackcurrant-iba.com/blackcurrants-france/
Germany	8,000	1,500	www.blackcurrant-iba.com/blackcurrants-germany/
Japan	7	7	www.blackcurrant-iba.com/blackcurrants-japan/
The Netherlands	1,200	180	www.blackcurrant-iba.com/blackcurrants-netherlands/
New Zealand	8,000	1,300	www.blackcurrant-iba.com/blackcurrants-nz/
Norway	600	200	www.blackcurrant-iba.com/blackcurrants-norway/
Poland	120,000	34,000	www.blackcurrant-iba.com/blackcurrants-poland/
Ukraine	27,000	5,000	www.blackcurrant-iba.com/blackcurrants-ukraine/
United Kingdom	13,000	2,000	www.blackcurrantfoundation.co.uk/

with a range from 80 to 476 mg/100 mg fresh weight (FW; Nour et al., 2013). A study, which was conducted in New Zealand, compared the chemical composition of eight juices (Magnus, Ben Ard, Ben Rua, Blackadder White, Ben Hope, L410, L406, and L700) from New Zealand BC cultivars (Parkar, Redgate, McGhie, & Hurst, 2014). It is evident in this work that the rutinoside forms of delphinidin and cyanidin make up the majority of ANC present. The cultivar with the highest concentrations of delphinidin 3-*O*-glucoside (D3G) and delphinidin 3-*O*-rutinoside (D3R) was L406 (631 and 2,559 μg/mL,

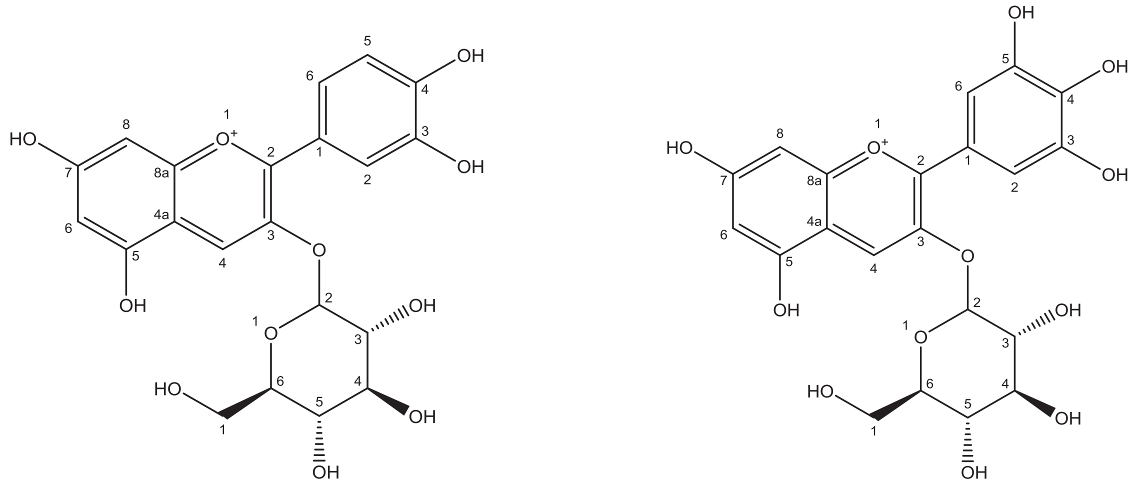
Table 2–Sources for blackcurrant berries (fresh and frozen), extracts, powders, plants, and pomace.

Company and production region	Products	Contact information
Highland Valley Farm, WI, USA	Fresh and frozen berries	87080 Valley Rd, Bayfield, WI 54814 (715) 779–5446
CurrantC, Staatsburg, NY, USA	CurrantC Black Currant Syrup, quick-dried black currants, black currant vinegar, black currant honey, preserves, nectar/juice, fresh berries, frozen berries, and plants	59 Walnut Lane Staatsburg, NY 12580 (845) 266–8999
Artemis International, IN, USA	Powders	3711 Vanguard Drive, Fort Wayne, Indiana 46809 (260) 436–6899
ActiveMicro Technologies, Ribes nigrum (Black Currant) Fruit Extract	PhytoCide Black Currant Powder (powders for use as antimicrobial agent in cosmetics and personal care products)	107 Technology Drive, Lincolnton, North Carolina, USA 28092 (704) 276–7086
New Zealand Blackcurrant Co-operative, Nelson, New Zealand (the largest juice producer in NZ)	Juice concentrate, individually quick-frozen berries, block frozen berries, puree, and single strength juice	17 Bullen Street, Tahunanui, Nelson 7011, New Zealand +64-3-548-5130
Sujon, Nelson, New Zealand (frozen fruit and powder producer in NZ)	Frozen berries and powder	17 Bullen Street, Tahunanui, Nelson 7011, New Zealand
Barker's of Geraldine, NZ	Squeezed NZ Blackcurrants Over 750 blackcurrants are squeezed into each bottle—a blend of the Magnus and Ben Rua blackcurrant varieties. Barker's blackcurrant syrups only contain New Zealand squeezed blackcurrants	Barker's of Geraldine Shop Four Peaks Plaza 76B Talbot Street Geraldine South Canterbury 7930 New Zealand
BlackMax Performance Nutrition, LTD (a NZ company selling blackcurrant powder for sports benefits)	Blackmax 300 g performance nutrition	16 Hinepango Drive, RD 3, Blenheim 7273, New Zealand 027-864-9164
NZP, New Zealand (the largest producer of powder in NZ)	Freeze-dried extract powders	68 Weld Street, RD 2, Palmerston North 4472, New Zealand +64-6-952-3800
CurraNZ, New Zealand (a UK company making products from NZ fruit powder)	CurranNz (extract capsules)	Curranz Ltd, 330 Parnell Road, PO Box 106109, Auckland, 1143, New Zealand
Just the Berries, New Zealand & Japan (a US company making products from NZ blackcurrants—esp eye health in Asia)	Anthocyanin extract powders (Antho Tex 35), juice powders, blackcurrant seed oil, blackcurrant brix 65, blackcurrant brix 68, infused dried fruits, puree, juices (functional and consumer), antiflu drinks, and antiflu candy	Japan Just the Berries Research Co., Ltd. Showa Bldg 9F 2-7-17Jimnocho, Kanda Chiyoda-ku, Tokyo 101-0051 Japan Just the Berries PD Corporation Address: 777 S.Figeuroa St, Suite 3775 Los Angeles, CA 90017
Berrico Food Company, the Netherlands	Dried fruit	PO Box 2296, 8203 AG Lelystad, Nederland's +31-0-320-266-055
Lemon Concentrate, Spain	Concentrate and pomace	Avenida Virgen del Rosario, 30012 Murcia, Spain +34-665-060-904

respectively). The cultivar with the greatest concentration of cyanidin 3-*O*-glucoside (C3G) was Ben Ard (314 µg/mL) and for cyanidin 3-*O*-rutinoside (C3R) it was L700 (3,138 µg/mL; Parkar et al., 2014). Other research on the ANC content of New Zealand BC cultivars compared with Non-New Zealand cultivars arrived at a similar conclusion and determined that New Zealand BC cultivars possess approximately 1.5 times more ANC (Schrage et al., 2010). Total ANC from 107 genotypes of *Vaccinium L.*, *Rubus L.*, and *Ribes L.* were evaluated and it was demonstrated that the concentration of ANC in BC is significantly affected by berry size (Moyer, Hummer, Finn, Frei, & Wrolstad, 2002). Variances among cultivars suggest that more research is needed to determine which cultivars contain the highest concentrations of these beneficial bioactive compounds. According to Nour et al. (2013), who performed a maceration of the berries in food grade ethanol (40%, 60%, or 96%), the compounds found in BC were D3G, D3R, C3G C3R, petunidin 3- *O*-rutinoside, pelargonidin 3-*O*-rutinoside, peonidin 3- *O*-rutinoside, petunidin 3-(6-coumaroyl) glucoside, and cyanidin 3-(6-coumaroyl) glucoside (Table 3). Of the three different extractions (40%, 60%, and 96%), 60% ethanol was able to extract the highest concentrations of the four major ANC from all three cultivars, except for D3R (Nour et al., 2013). After performing ANC extraction with an 80% (v/v) aqueous methanol solution with 0.1% HCl, Lee et al. (2015) reported that the contents of ANC in BC were D3R (55.2%), cyanidin-3-*O*-rutinoside (23.2%), and delphinidin-3-*O*-glucoside (18.8%). This suggested that ethanol was more effective than acidified methanol for extraction of more diverse forms of ANC from BC (Table 3). Figure 5 presents an HPLC profile at 520 nm for the characterization of ANC showing the presence of D3G, D3R, C3G, and C3R (Buchert et al., 2005). According to the study by Nour et al. (2013), the concentration of total phenolics in BC ranged between 1,261 and 1,694 mg eq of gallic acid/L with the lesser values being from the 40% ethanol extraction and the higher values from the 96% ethanol extraction. PAC present in BC are polymers that can be divided into two categories, procyanidins (PC) and prodelphinidins (PD; Figure 4; Laaksonen, Salminen, Mäkilä, Kallio, & Yang, 2015). PC are polymers made up of catechins (+) and epicatechins (–) and PD are also polymers made up of gallocatechins (+) and epigallocatechins (–) (Figure 4; Laaksonen et al., 2015). ANC are naturally hydrophilic and therefore have limited application potential in both foods and

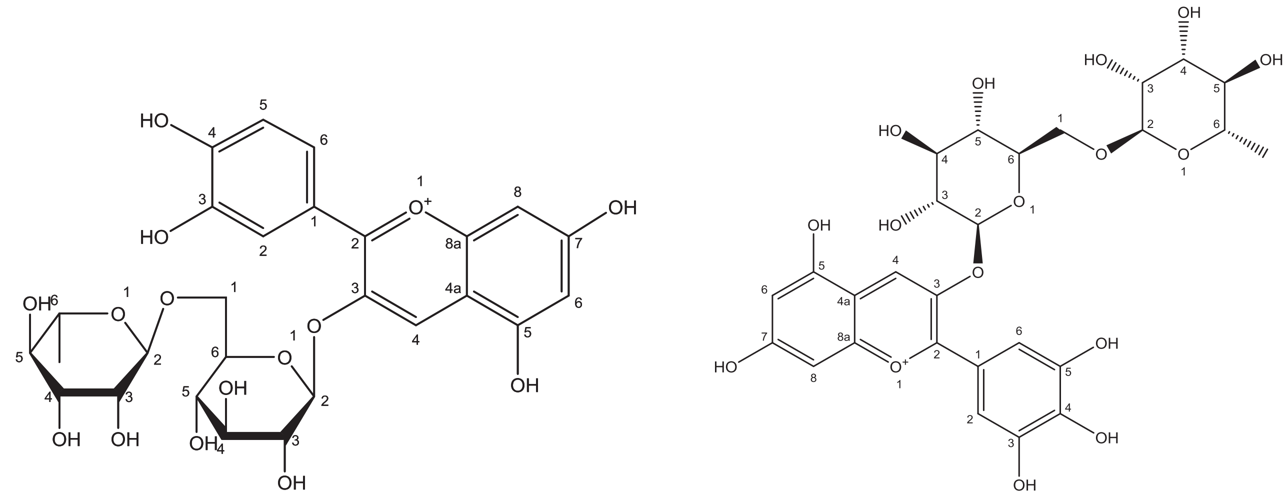
Figure 2–Examples of some commercial blackcurrant beverages. (A) Products available in the United States. (B) Products available elsewhere.

cosmetics that contain fats or oils (Cruz et al., 2018). However, there has been research done to try to improve the performance, stability, formulation properties, and color of ANC from BC. One particular study sought to increase the stability of ANC from BC without a loss in bioactivity (Cruz et al., 2018). This study used the enzyme *Candida antarctica* lipase B and octanoic acid to lyophilize and esterify ANC from BC. BC extracts (BCE) from skins were obtained (Table 3) and purified to only contain the four major monomeric ANC D3R [43.3%], C3R [34.0%], C3G [7.0%], and D3G [15.7%]; Cruz et al., 2018). This



Cyanidin 3-*O*-glucoside

Delphinidin 3-*O*-glucoside



Cyanidin 3-*O*-rutinoside

Delphinidin 3- *O*-rutinoside

Figure 3–The chemical structures of the four main anthocyanins found in blackcurrants.

work concluded that only the glucoside forms of cyanidin and delphinidin were acylated by the enzymes and not the rutinoside forms. A different study found that by using lauric acid, each of the four major ANC was monoacylated successfully without an adverse effect on relative proportions (Yang, Kortesniemi, Ma, Zheng, & Yang, 2019). Each of the acylations was noted at the 6′′–OH position and at the 4′′–OH position of the glucosides and rutinosides, respectively (Yang et al., 2019). This process succeeded in enhancing the lipophilicity of the compounds, which makes them more compatible for use in lipid-based foods and cosmetics. Although one group of researchers was able to alter the hydrophilicity of ANC from BC, results still suggest that more research is needed to address the hydrophilicity of ANC from BC so that the food and cosmetics industries may better utilize them.

BC are bitter and astringent; because of this, large amounts of sugar are often added to BC products to offset the bitterness and astringency. This can be problematic for companies seeking to appeal to health-conscious consumers. Pectinolytic enzymatic treatments, which increase juice yields, also increase the perception of bitterness and astringency because the enzymes increase the mean degree of polymerization of PAC (Laaksonen et al., 2015). Additionally, astringency is related to the mean degree of polymerization (mDP) of PAC, which are oligomeric and polymeric tannins with different flavan-3-ol units (Laaksonen et al., 2015). The mDP is an indicator of the average number of flavan-3-ol monomers that make up the condensed tannins (Laaksonen et al., 2015). Epicatechins, which are subunits of PC, are thought to be more bitter and astringent than catechins at equal concentrations. The reason for the perception of these bitter and astringent flavors is still not fully understood (Laaksonen et al., 2015). It has historically been hypothesized, and generally accepted, that this phenomenon is due to polymeric tannins binding

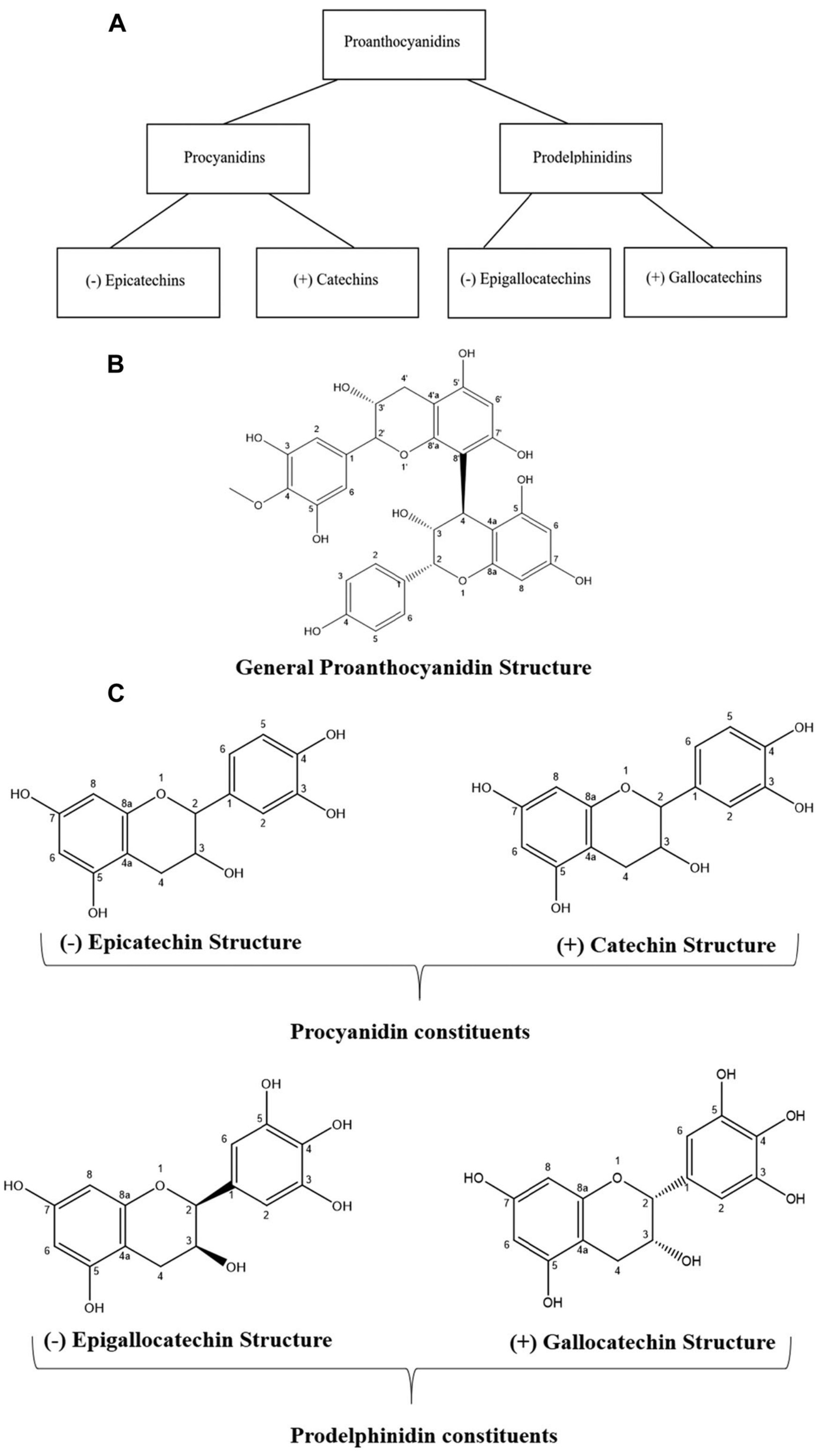


Figure 4–A schematic diagram of the subgroups of proanthocyanidins and their chemical structures.

and precipitating salivary proteins, which in turn are perceived as a rough and drying sensation in the mucous membranes (Laaksonen et al., 2015). It is believed that proline clusters, and possibly nearby residues, are the probable sites for the PC interactions with salivary proteins (Soares et al., 2018). After analyses of five different cultivars, Mortti, Mikael, Marski, Ola, and Breed15, it was discovered that samples that had undergone an enzymatic treatment prior to processing showed not only a significantly higher mDP but also demonstrated higher concentrations of PAC (both PC and PD; Laaksonen et al., 2015). BC juices that contain

Table 3–Blackcurrants materials, extraction methods, solvents, and compounds obtained.

Starting materials and extraction methods	Solvents	Compounds extracted	References
Whole fresh blackcurrant berries were macerated. Phenomenex Gemini C18 (150 × 4.60 mm, 3 μm) column, protected with Phenomenex security guard column	Food grade ethanol (40%, 60%, or 96%), 1% formic acid with 5% acetonitrile in water, and 100% acetonitrile	Delphinidin 3-glucoside, delphinidin 3-rutinoside, cyanidin 3-glucoside, cyanidin 3-rutinoside, petunidin 3-rutinoside, pelargonidin 3- rutinoside, peonidin 3-rutinoside, petunidin 3-(6-coumaroyl) glucoside, and cyanindin 3-(6-coumaroyl) glucoside	Nour et al. (2013)
Whole freeze-dried blackcurrant berries. Sep.-Pak C18 Plus Short SPE cartridge (Waters, Milford, MA, USA)	Aqueous methanol solution 80% (v/v) with 0.1% HCl and rinses of water, ethyl acetate, and acidic MeOH	Delphinidin-3-*O*-rutinoside (55.2%), cyanidin-3-*O*-rutinoside (23.2%), and delphinidin-3-*O*-glucoside (18.8%)	Lee et al. (2015)
Blackcurrant juice	Acidified MeOH and ethyl acetate	Delphinidin glycosides, cyanidin glucosides, glucosides of anthocyanins, rutinosides of anthocyanins, anthocyanin degradation products, flavonol glycosides, flavonol aglycones, myricetin glycosides, quercetin glycosides, kaempferol glycosides, isorhamnetin glycosides, glucosides of flavonols, rutinosides of flavonols, and various hydroxycinnamic acids	Mäkilä et al. (2017)
Blackcurrant pomace. SFE-CO2; Helix 1 SFE system with a 50 mL stainless cylindrical extractor vessel (i.d. = 14 mm, length = 320 mm) filled with 15 g BC pomace, Soxhlet	SFE-CO$_2$, hexane, acetone, ethanol:water, pressurized ethanol, and pressurized water	Fatty acids (myristic, palmitic, palmitic, palmitoleic, heptadecanoic, stearic, oleic, linolelaidic, linoleic, arachidic, γ-linolenic, cis-11, 14-eicosenoic, linolenic, cis-11, 14-eicosadienoic, behenic, cis-11, 14,17-eicosatrienoic, and lignoceric)	Basegmez et al. (2017)
Blackcurrant juice. Sephadex LH-20 gel, Waters Acquity UPLC BEH Phenyl (1.7 μm, 2.1 × 100 mm), Waters Delta 600 with Fraction Collector III, Phenomenex Gemini (150 × 21.2 mm, 10 μm, C18, 110 Å	Acetonitrile and formic acid	Proanthocyanins, procyanidins (with varying mDP) and prodelphinidins (with varying mDP)	Laaksonen et al. (2015)
Blackcurrant pomace. Separation by centrifugation	HCl/KCl buffer (pH 2.0, 0.1 M), 95% ethanol, isopropanol, and deionized water	Acid-soluble pectins	Alba et al. (2018)
Blackcurrant pomace. Separation by centrifugation	0.25% w/v ammonium oxalate (pH 4.6); solid to liquid ratio 1:40	Calcium-bound pectins	Alba et al. (2018)
Blackcurrant pomace. Separation by centrifugation	6% v/v H_2O_2 (60 pH 11.5) and 3 g/L of $NaBH_4$; solid to liquid ratio 1:20	Alkali-soluble lignin, alkali-soluble hemicelluloses, and cellulose	Alba et al. (2018)
Solid-phase extraction Amberlite XAD-7HP (120 g) column, rotary evaporator, and high vacuum	Acidified water (0.01% v/v HCl) and acidified ethanol (0.01% v/v HCl)	Blackcurrant skins yielded a blackcurrant extract (amorphous violet solid or purified blackcurrant extract)	Cruz et al. (2018)
Blackcurrant pomace. Solid-phase extraction (Amberlite XAD-7HP, 60 g).	Water acidified with 0.01% v/v HCl	Dark violet amorphous solid	Rose et al. (2018)
Blackcurrant pomace. Fruit to solvent ratio = 1:3. Ultrasound-assisted extraction with an amplitude range between 0% and 100% (UP100H, Teltow, Germany), 0.50, 5.25, and 10 min.	Water, 50:50 water with ethanol (96%), (85:15) water with citric acid (1 M, 2 M, 1.5 M, and 3.0 M), and (85:15) ethanol and HCl (1.5 M)	Sonicated extract	Archaina et al. (2018)
Blackcurrant skins. Separation with Buchner funnel loaded with RP-C18 silica gel and lyophilization	Dissolved in 100 mL acidified water (2% HCl), extracted with ethyl acetate (3 × 100 mL), elution solvent (water/methanol 70:30 (v/v) and acidified (2% HCl)	Purified blackcurrant extract (amorphous violet solid) yielded a dark red solid	Cruz et al. (2018)

higher concentrations of PAC could be viewed as undesirable due to their flavor, despite their benefits (Laaksonen et al., 2015). This does, however, offer unique opportunities for extractions because the diversity of ANC in BC is not complex. Sensory evaluations of other parts of BC have also been conducted to explore the use of BC pomace (BCP) as a source of dietary fiber. In one study, consumers were blindly tested for acceptance of a 50% wheat flour, 30% buckwheat flour, and 20% corn flour crackers compared with

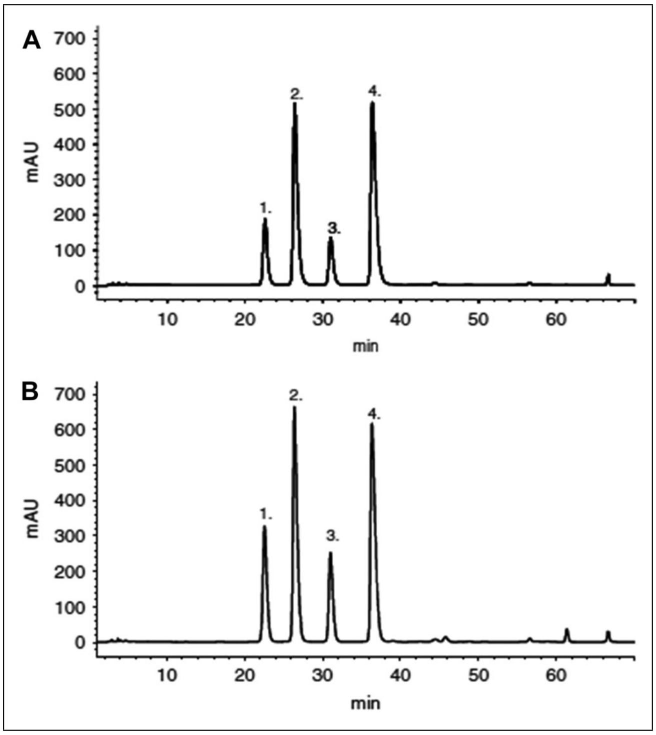


Figure 5–A representative HPLC chromatogram showing the peaks at 520 nm and retention times of the four major anthocyanins found in blackcurrants. These chromatograms were made before and after a pectinase (Pectinex BE-3L) treatment on blackcurrant juice (Buchert et al., 2005). Reproduced with permission from Wiley Imprint/Publication.

crackers made up of the same ingredients with the addition of BC pomace (10%, 20%, and 30%; Schmidt, Geweke, Struck, Zahn, & Rohm, 2018). The 20% pomace cracker scored a 4.17 on an acceptance scale of 1 to 7, whereas the reference scored a 4.37 on the same scale (Schmidt et al., 2018). However, the 30% pomace crackers produced a stiffer dough, which led to a lower hardness trait due to high water absorption; thus, the pomace restricted the ability of a strong protein network to form. The poor formation of a protein network also resulted in at least a 57% decreased volume of the 20% and 30% pomace crackers compared with the 10% pomace and reference crackers (Schmidt et al., 2018). Changes to the color of the cracker were also noted as the BC pomace changed the color of the crackers from the traditional light tan color to a deep shade of red. There were only slight differences between the structures and appearances of the 20% and 30% pomace crackers compared with the reference with no pomace and 10% pomace crackers (Schmidt et al., 2018). Despite this, there was virtually no difference between consumer preferences of crackers, which shows BC pomace is a viable option to replace a significant amount of wheat flour in baked goods (Schmidt et al., 2018). The ANC in BC berries and juices provide rich colors to commercial products, some of which are recorded in Table 4. The color parameters of some commercially available BC beverages were measured in our laboratory using the CIELAB color scale. Both hue angle and chroma were calculated using the $L^*a^*b^*$ values and the following formulas: Chroma $C^* = \sqrt{(a^*)^2 + (b^*)^2}$ and Hue angle $h_{ab} = \tan^{-1}(\frac{b^*}{a^*})$. Results are presented in Table 4. Chroma is the saturation or richness of a color and hue angle referrers to the color perceived based on the wavelength (Cortez, Luna-Vital, Margulis, & Gonzalez de Mejia, 2017).

Environmental and Variety Impact on Chemical Composition

Although it is clear that there are several benefits to be gained by using BC in food products, both the environment and genetics play critical roles in the production, chemistry, and nutritional quality of the BC fruits. A study, which investigated the environmental effects on BC, was conducted in Denmark (55° 18′ N 10° 26′ E) from October 2014 to April 2015. It was demonstrated in this study that there was a significant decrease in the number of flowers when the experimental plots were warmed to an average temperature of 1.3 °C greater than the control plot (ambient temperature; Andersen et al., 2017). The temperature of the control plots did not vary the height of the plants; however, air temperature of warmed plots led to lower height of 50 and 80 cm (on average by 0.4 and 0.7 °C, respectively). Both cultivars (Narve Viking and Zusha) grown in ambient temperatures produced more flowers per plant (451 and 491, respectively) and had higher berry yields, total berries per plant, and produced berries with greater individual weights (Andersen et al., 2017). When comparing each of these two cultivars, warmer temperatures did not physically damage them. This ultimately led to the conclusion that the environment does not lead to a direct correlation between the crop and production, but rather has an effect on the genes of growth and development. This, consequently, leads to changes such as fewer flowers and less beneficial health properties, for instance, a decrease in flavanol and ANC content (Andersen et al., 2017). Not only does temperature affect decreasing the aforementioned bioactive compounds, but there was a clear correlation between higher concentrations of gallic acid and the colder temperatures in the control plots (Andersen et al., 2017). Production of BC berries depends on the genetics of each cultivar and the temperature of the growing environment. High temperatures during the growing season are also associated with the inhibition of various biochemical processes during BC development, which in turn decreases the amount of ascorbic acid produced (Woznicki et al., 2017). High temperatures (12 to 24 °C) have been shown to reduce the amount of ascorbic acid and the overall sugar content by 27% in BC (Woznicki et al., 2017). However, higher temperatures do not diminish all desirable properties of BC as citric acid concentrations were increased (Woznicki et al., 2017). It can be concluded from these studies that growing BC plants in colder climates produce berries, which have higher concentrations of beneficial bioactive compounds such as phenolics, which add value to an already high-value fruit. Another recent study also examined the effects of growing temperature and day length from a metabolomics approach (Allwood et al., 2019). The recorded data from this work confirmed earlier observations by Woznicki et al. (2017) by concluding that growing temperature significantly affected a total of 365 metabolites constituting a wide variety of chemical classes. A comparison between ambient conditions and controlled conditions (planted in pots outdoors with ambient summer conditions, 59°40’N) demonstrated that ripening BC berries had accumulated a total of 34 additional metabolites under ambient conditions, the majority of which were ANC and flavonoids (Allwood et al., 2019). Additionally, a significant upregulation of 100 metabolites (linear increase) was noted with increased cultivation temperatures, and 42 metabolites experienced a linear decrease. It is particularly interesting to note that phenylalanine was one of the upregulated metabolites (with increased cultivation temperatures) and it is also the main precursor for the synthesis of flavonoids. However, it is not the limiting factor for

Table 4–Color parameters of commercially available blackcurrant beverages.

Beverage	Manufacturer and Origin	Ingredients	L^a	a^a	b^a	Hue Angle	Chroma	Color Square
Mathilde Cassis	Ars-sur-Formans, France	Noir de Bourgogne and Blackdown	16	38	20	28 ± 0.1	43 ± 0.01	🟥
Briottet Crème de Cassis	Dijon, France	Blackcurrants, sugar, and alcohol	11	32	13	22 ± 0.01	34 ± 0.0	🟫
Cassis Lambic	Vlezenbeek, Belgium	Barley, unmalted wheat, blackcurrant juice, aged hops, and wild airborne yeast.	47	36	47	53 ± 0.02	60 ± 0.04	🟧
Pomona Kir	Pomona, IL, USA	Blackcurrants and apples	60	31	53	60 ± 0.02	61 ± 0.04	🟧
Cider Kir	Nelson, New Zealand	Carbonated cider, 84% apple juice, 10% blackcurrant (Upper Moutere) juice, 5% water, 1% cane sugar, and ascorbic acid	39	47	46	44 ± 0.02	66 ± 0.01	🟥
Wasosz Beer	Konopiska, Poland	Water, pilsner malt, caramel malt, hops, yeast, and currant juice	60	24	42	60 ± 0.04	49 ± 0.0	🟧
Black Mead	White Winter Winery, Iron River, WI, USA	Honey, blackcurrant, and natural flavors	29	40	42	47 ± 0.02	58 ± 0.01	🟫
Ribena	Stockley Park, Uxbridge, UK	Water, sugar, blackcurrant juice from concentrate (23%), citric acid, vitamin C, preservatives (potassium sorbate, sodium bisulfite), and color (anthocyanins)	69	35	17	26 ± 0.01	39 ± 0.0	🟥
Fortuna Czarna Porzeczka Nektar	Warsaw, Poland	Water, blackcurrant juice from concentrate, sugar, and natural blackcurrant flavor	27	44	38	40 ± 0.01	58 ± 0.0	🟥
Black Box Cabernet Sauvignon[a]	Madera, CA, USA	Red wine from grapes	13	35	15	23 ± 0.01	38 ± 0.01	🟫

[a] Black Box Cabernet Sauvignon red wine added for a comparison between blackcurrant products and a red wine. Ribena was diluted 1:4 with water.

synthesis efficiency (Allwood et al., 2019). A study conducted in New Zealand (Inst. for Plant and Food Research) concluded that BC juice from BC grown in New Zealand contained approximately 1.5 times more ANC than those not grown in New Zealand (Schrage et al., 2010). Although this information does provide great insight into ideal BC growing conditions for the maximization of various polyphenolic compounds, it also offers producers an opportunity to adjust growing methods as temperatures become extreme with the changing global climate. Allwood et al. (2019) demonstrated that under high temperature, BC present lower concentration of ANC; so, these values will be lower in years with extreme hot summers. Concentrations of polyphenols vary depending on the cultivar, so more research is need to find out which cultivars contain the highest concentration of bioactive compounds.

Technological Methods for BC Processing

Enzymatic treatments

Generally, the reasons for berry fruit processing are to maximize juice yields, inactivate microorganisms, inactivate enzymes, and to maintain the sensory qualities of the finished product (Mäkilä, Laaksonen, Kallio, & Yang, 2017). The use of enzymatic treatments in juice production is quite common, especially in the processing of berry juices because it can increase juice yields up to approximately 91% (Laaksonen et al., 2014; Table 5). These treatments improve the juice yield, decrease the viscosity of the juice, and also significantly increase the extraction of bioactive compounds such as phenolics (Bender, Killermann, Rehmann, & Weidlich, 2017; Laaksonen et al., 2014). The contents of PC and PD are significantly higher with enzymatic maceration than without (Laaksonen et al., 2015). A possible explanation for this phenomenon is that bioactive compounds, which are trapped in the networks of the pectins, are liberated with the effects of the enzymes. Employment of the enzymatic process increases the nutritional value of BC juices because of the increase in what is an already high concentration of bioactive compounds. A Finnish research group demonstrated a 151 mg/100 mL increase in total PAC and a 121 mg/100 mL increase of total PD with the utilization of an enzymatic process for BC juice production (Laaksonen et al., 2015). In 2017, a different study demonstrated that the total ANC concentration of BC juice could be increased by 584 mg/100 g before pasteurization and 524 mg/100 g after pasteurization with the use of enzymatic pectinases (Mäkilä et al., 2017). Enzymatic treatments achieve these higher extraction rates as a result of the enzymes demolishing cell wall structures, which happens by cleaving pectins and causing the degeneration of soluble pectins (Bender et al., 2017). Berries are known to have higher viscosities during processing for juice making, than other fruits. After the berries have been crushed, the higher viscosity complicates the pressing process and causes a great deal of inefficiency, which is why it is necessary to use enzymatic treatments in the production of berry juices (Bender et al., 2017).

Processing Methods

BC are relatively expensive fruits containing concentrated amounts of compounds in the skins and seeds that are beneficial to health, all of which are typically discarded. Included in these compounds are not only polyphenols but also polyunsaturated

Table 5–Examples of processing methods, treatments, and changes in composition of blackcurrant juice.

Processing methods	Treatments	Changes in composition	References
Enzymatic maceration	Pectinase 714L, Biocatalysts Ltd., Cardiff, UK (dosage = 57 mg of enzyme/380 g of berry mash	Increase in mDP (increases astringency and bitterness)	Mäkilä et al. (2017)
Heat and enzymatic treatments	50 °C, 85 °C, Pectinex® Ultra Color	Heat treatment had no effect on juice yield; enzymatic treatment reduced turbidity and viscosity	Bender et al. (2017)
Enzymatic maceration	Pectinase 714L, Biocatalysts Ltd., Cardiff, UK (dosage = 57 mg of enzyme/380 g of berry mash	Increase in procyanidins and prodelphinidins (dimers and trimers)	Laaksonen et al. (2015)

All enzymatic treatments increased overall juice yields. Mean degree of polymerization (mDP).

fatty acids (PUFA), tocopherols, phytosterols, polycosanols, and fiber (Basegmez et al., 2017). One way of maximizing the many benefits of BC is to find ways in which the BCP can be processed and repurposed for use. Pomace is the material that remains after the BC have been processed for juice, which consists mainly of skins and seeds. At present, much of the pomace, which is acidic, is discarded as waste and has the potential to become an environmental hazard when it is disposed of in landfills (Basegmez et al., 2017). In addition, it is quite wasteful to discard such an enriched material. Basegmez et al. (2017) discovered a remedy for these issues that has many advantages. It is the use of supercritical fluid extraction with carbon dioxide (SFE-CO_2) along with response surface methodology and central composite design (Basegmez et al., 2017; Table 3). This is a green technology method for the recovery of high-value fractions. This process is rapid, automatable, selective, nonflammable, involves no toxic solvents, does not allow exposure to light or oxygen during extraction, and produces solvent-free extracts and residues (Basegmez et al., 2017). As the name implies, SFE-CO_2 involves the use of carbon dioxide, which is of low toxicity and generally recognized as safe (GRAS) by the Food and Drug Administration (Basegmez et al., 2017). Another study performed ultrasound-assisted extractions (UAE) of BCP by using water acidified with citric acid (Archaina et al., 2018). In this work, it was documented that UAE is a viable method for the extraction of bioactive compounds from BCP. Furthermore, in this same study, the investigators used a maltodextrin carrier matrix to spray dry the extracts. It was concluded in this research that the obtained powder maintained high levels of total ANC and total phenolic contents (63.01 ± 1 mg eq C3G/100 g dry material and 116.87 ± 5 mg eq gallic acid/100 g dry material, respectively; Archaina et al., 2018). Conventional drying methods, such as convective drying, freeze-drying, and microwave vacuum drying, offer less expensive alternatives to SFE-CO_2 for the recovery and use of BCP; however, they do have some limitations. It was discovered that the dehydration of BCP by freeze-drying reduced the total phenolics by 76% and with convective drying (90 °C) by 90% compared to fresh pomace (Michalska et al., 2017). Interestingly, samples that were dried using convection exhibited the most significant decrease in total flavonols when dried between 50 and 60 °C (Michalska et al., 2017). The use of BCP as a means of adding fiber to processed foods offers an attractive incentive for BC producers and processors alike. A recent characterization study on BCP sourced from two different countries (Lucozade-Ribena-Suntory, UK and Green-Field Natural Ingredients, Warsaw, Poland) reported that 25% to 30% of BCP is soluble dietary fiber (SDF; for example, pectin and some hemicelluloses), whereas approximately 47% is insoluble dietary fiber (IDF; for example, cellulose or lignin; Alba et al., 2018). Pure IDF was measured as being approximately 61%. Ratios for IDF/SDF were calculated for the BC from the United Kingdom and the BC from Poland as 1.9 and 1.6, respectively (Alba et al., 2018). The main cell wall component noted in this research was Klason lignin, which was the major insoluble fiber in both BCP (Alba et al., 2018). This characterization of BCP was preceded by fractions of constituent soluble and insoluble fractions followed by extractions of pectins (acid soluble and calcium soluble), alkali-soluble lignin, alkali-soluble hemicelluloses, and cellulose (Table 3; Alba et al., 2018). This study confirmed that downstream waste from BC processing could be fractioned, used as food ingredients for added benefits, and potentially increasing the ability to make health claims. Another study was able to demonstrate how BCP (skins and other solid material that remain after juice processing) can be used to create hair dyes that are an intense blue color by employing entirely sustainable technology (Rose et al., 2018). It should also be noted that the resulting colorant was entirely biodegradable, which is attractive for consumers (Rose et al., 2018). A similar study found an environmentally friendly way to extract ANC from BC waste to be used as colorants (Farooque, Rose, Benohoud, Blackburn, & Rayner, 2018).

Health Benefits of Bioactive Compounds from BC

The study of polyphenols and ANC has been well documented; however, there are still many unknown factors regarding health benefits. ANC account for 90% of the total polyphenols in BC and as much as 73% of the consumed ANC may reach the colon and be broken down by microbes (Parkar et al., 2014). One promising discovery regarding ANC from BC is that they have the ability to inhibit the adhesion of *Salmonella enterica serovar Typhimurium* to Caco-2 cells by up to 39%, which would be advantageous for food industry processing. This same study confirmed strong dose-dependent correlations with D3G and C3R from BC juice and the ability to inhibit the adhesion of *Salmonella enterica serovar Typhimurium* to Caco-2 cells (Parkar et al., 2014). In addition to possessing antimicrobial properties, BC juices and PAC-rich BCE have been proven to be beneficial for asthma and airway-related issues. The mechanism is by the downregulation of Th2 cytokines, cytokines, cyclooxygenase, and the modulation of CCL 1 and CCL secretion (Table 6; Hurst et al., 2010; Nyanhanda et al., 2014; Shaw, Nyanhanda, McGhie, Harper, & Hurst, 2017). Xu et al. (2018) characterized the effects of ultrasound irradiation on the bioactivities of BC polysaccharides. During this characterization process, three different BC polysaccharide solutions were assessed for the effects from ultrasound treatments and its impact on antioxidant activity, free radical scavenging activities, inhibition of lipid peroxidation, protection from DNA damage, and the inhibition of α-amylase and α-glucosidase activities. It was concluded that the higher wattage of ultrasound power produced

Table 6–Examples of health benefits and associated compounds found in blackcurrant products.

Blackcurrant product used	Compounds	Properties beneficial to health	References
Whole berry and juice	Cyanidin 3-glucoside, cyanidin 3-rutinoside, delphinidin 3-glucoside, delphinidin 3-rutinoside, and ascorbic acid	Antioxidant (reduction in oxidative stress by scavenging of free radicals)	Bender et al. (2017), Braakhuis et al. (2014), and Lyall et al. (2009)
		Anti-inflammatory (*in vitro*)	Benn et al. (2014), Lyall et al. (2009), and Shaw et al. (2017)
		Hypocholesterolemic (mice & rats)	Cook, Myers, Gault, Edwards, and Willems (2017a)
		Increase in cellular LDL uptake, decrease postprandial blood glucose	Kim et al. (2018)
		Phytoestrogenic (*in vitro*), ameliorate glucose tolerance (mice and rats and humans)	Nanashima et al. (2018)
		Increases fat oxidation (humans)	Cook, Myers, Gault, Edwards, and Willems (2017b) and Strauss et al. (2018)
		Biosynthesis of collagen and production of some peptide hormones	Woznicki et al. (2017)
Seeds	Gamma linoleic acid	Antioxidant	Nour et al. (2013)
		Potential attenuation of inflammatory responses	Sergeant, Rahbar, and Chilton (2016)
Leaves	Derivatives of quercetin and kampferol, prodelphinidins, chlorogenic acid, caffeic acid, gallic acid, ferulic, and gentisic acid	Antioxidant	Ferlemi and Lamari (2016), Tabart et al. (2012), and Teleszko and Wojdyło (2015)

Each sample description may also represent an extract from that particular source material. See text for more examples.

a higher reducing sugar content along with improved thermal stability. Although there was an increase in reducing sugar content, six species of monosaccharides (galacturonic acid, galactose, mannose, glucose, arabinose, and rhamnose) were found in the treated sample. The same six monosaccharides were also found in the control suggesting that the ultrasound treatments did not produce any significant structural changes. However, the study concluded that ultrasound irradiation improves the antioxidant capacity, and the percent inhibitions of both α-amylase and α-glucosidase, likely because there was a degradation of polysaccharides present. The degraded polysaccharide U-600 W ($M_w = 1.32 \times 10^4$ kDa) ultrasound treated sample exhibited the best results for all assays performed when compared to the polysaccharide that received a lower wattage treatment.

Ashigai et al. (2018) demonstrated the effectiveness of oral intake of BC cassis polysaccharide on reducing skin dehydration caused by ultraviolet light in mice. They also reported decreases on markers of inflammation, such as those of interleukin-6 and matrix metalloprotein transcription levels in the skin of hairless mice.

BC are high in ascorbic acid (50 to 280 mg/100 g or 300 mg/100 mL of juice), this together with a high flavonoid content bolsters the antioxidant capacity of the berries and increases their potential to promote health benefits (Bladé et al., 2016; Castro-Acosta et al., 2016; Lee et al., 2015; Nour et al., 2013; Woznicki et al., 2017). By comparison, BC have a much higher concentration of ascorbic acid than both raspberries and blueberries (Bender et al., 2017). According to Nour et al. (2013), ascorbic acid concentration can be found in a range from 50 to 280 mg/100 g FW, adding to the attractiveness of BC for the food and beverage industries. Not only is ascorbic acid an antioxidant, but it also facilitates the biosynthesis of collagen, and aids in the production of some peptide hormones (Woznicki et al., 2017). The antioxidant properties of BC are largely attributed to phenolic compounds (such as ANC), which act as either hydrogen donors or transfer electrons, depending on the ANC (Blando et al., 2018; Wang, Cao, & Prior, 1997). ANC antioxidant activity is directly related to their chemical structure. Differences in antioxidant activity in anthocyanidins can be attributed to differences such as the type, position, and number of methyl and hydroxyl groups (Blando et al., 2018). Polyphenols are known to be responsible for the scavenging, or trapping, of free radicals, which are responsible for oxidative stress. Results from the study by Nour et al. (2013) indicated that there was a high correlation ($r = 0.85$) between antioxidant activity and the total concentration of ANC (Table 6). Generally speaking, ANC are supposed to increase the antioxidant capacity; however, BC exhibit a lesser antioxidant capacity than both blackberries and blueberries (Lee et al., 2015). This reduced antioxidant capacity in BC can likely be attributed to the presence of other polyphenols that are not ANC such as phenolic acids, PAC, tannins, and flavonoids (Lee et al., 2015). Additionally, the lower antioxidant capacity of BC could also be attributed to the specific structures of the ANC present and perhaps steric hindrance by glycones attached to the B-ring (Lee et al., 2015). A different study found that the antioxidant capacity can be increased by first completing a mash enzymatic maceration of the berries (Bender et al., 2017). It has also been reported that BCE were able to produce hypocholesterolemic effects in mice with diet-induced obesity (Benn et al., 2014; Kim et al., 2018; Table 6).

Both animal and human studies reported the effects of BC and BCE on athletic training and performance. It was demonstrated that BC and BCE reduce oxidative stress–related injuries that cause fatigue and damage (Braakhuis, Hopkins, & Lowe, 2014; Hurst, 2015; Hurst & Hurst, 2013; Schrage et al., 2010). It has also been well documented that flavonoids protect retinal cell types from death due to oxidative stress (Kalt, Hanneken, Milbury, & Tremblay, 2010). This phenomenon can likely be explained by the fact that the highest metabolic rate of any tissue in the body is in the retina, which is susceptible to oxidative stress injury (Kalt et al., 2010). An *in vivo* study with mice and rabbits evaluated the ANC

Table 7–Examples of some commercially available blackcurrant products.

Name	Type of product	Origin	Ingredients	Health claims	Price in U.S. dollars
Monin blackcurrant syrup	Premium gourmet syrup	Clearwater, FL, USA	Pure cane sugar, water, and natural blackcurrant flavor	None	$9.95 for 750 mL glass bottle
St. Dalfour blackcurrant all natural fruit spread	Fruit spread	Chambord, France	Blackcurrants, concentrated grape juice, and fruit pectin	None	$9.89 for 283.5 g
Pepsi Co 1893 blackcurrant cola	Soda/soft drink	Purchase, NY, USA	Carbonated water, sugar, caramel color, natural flavor, phosphoric acid, sodium citrate, potassium sorbate, caffeine, gum Arabic, and kola nut extract	None	$1.79 for 355 mL
Gabriel Boudier crème de casis	Liqueur	Dijon, France	Blackcurrants, ethanol, and sugar	None	$32.99 for 375 mL
Ribena blackcurrant concentrate and ready to drink beverages	Drink	Uxbridge, England	Water, sugar, blackcurrant juice from concentrate (6%), vitamin C, citric acid, and color (anthocyanins)	Daily dose of vitamin C	$1.66 for 1 L
Harney and Sons Fine Teas blackcurrant tea	Tea	NY, USA	Black tea, currants, blackcurrant flavor, and contains natural flavors	None	$5.99 for 40 g
Standard Process blackcurrant seed oil supplements [a]Not FDA approved	Nutritional supplements	WI, USA	Blackcurrant seed oil, gamma-linolenic acid, gelatin, glycerin, and water	Encourages proper eicosanoid synthesis, supports the body's normal tissue repair process, normal blood flow, and healthy immune system function	$16.50 for 60 perles

[a]All prices listed were obtained in 2017.

content in eight parts of the eyes (cornea, sclera, choroid, ciliary body, iris, retina, vitreous, and lens) at various time intervals after being given BC juice powder (21.6% ANC) by oral administration (rats, 100 mg/kg body weight), intraperitoneal administration (rats, 108 mg/kg body weight), or intravenous administration (rabbits, 92.6 mg/kg body weight; Matsumoto, Nakamura, Iida, Ito, & Ohguro, 2006). The results of this study were that after oral administration, ANC were found intact in both the whole eyes and plasma. ANC reached a maximum concentration of 115 ± 32 ng/g in the whole eye after 30 min. The half-lives of ANC in the plasma and whole eye were 1.4 and 1.1 h, respectively. The majority of ANC were detected in the sclera with choroid and cornea (Matsumoto et al., 2006). After the intraperitoneal administration, the ANC concentration reached 4.99 ± 0.48 μg/g in the whole eye after 30 min, which was the maximum. The ANC concentration in the whole eye was two times greater than that of the plasma and the majority of ANC were found in the sclera and choroid. Intravenous administration results demonstrated that ANC found in the sclera and choroid had significantly lower concentrations and that higher concentrations were reported in the plasma (Matsumoto et al., 2006). The ANC concentrations of the rabbits' ocular tissues were determined and were ranked as follows: sclera > choroid > ciliary > body > aqueous humor > iris > cornea > retina > vitreous > lens, suggesting that there is an affinity between ANC and collagen fibers (Matsumoto et al., 2006). This study confirmed that ANC from BC juice (from powder) can pass through both the blood–retinal and blood–aqueous barriers in both rats and rabbits. These results are promising in that they suggest BC and BCE have the potential to be used as therapies for the treatment of ophthalmological diseases.

It was reported by Nanashima et al. (2018) that treatments with BCE increased collagen, elastin, and hyaluronic acid in human skin fibroblasts and ovariectomized rats. This study used normal human female skin fibroblast cells (TIG113), OVX female Sprague–Dawley rats (12 weeks old) that had their ovaries removed to simulate menopausal women, and sham surgery rats (Nanashima et al., 2018). The TIG113 cells were treated with BCE with 1.0 μg/mL for microarray gene expression profiling and either 1.0 μg/mL or 10.0 μg/mL for reverse phase polymerase chain reaction (RT-qPCR) assays. The rats were fed AIN-93M diets, with and without 3% BCE (Nanashima et al., 2018). Results from this study indicated that TIG113 cells that were exposed to BCE had similar effects to TIG113 cells that have been exposed to estradiol. The results from the OVX rat study indicated that the thickness of the collagen was significantly greater in those treated with 3% BCE (1,156 ± 36 μm) and in sham rats (845 ± 36 μm) (Nanashima et al., 2018). Therefore, it was made evident that BCE, particularly the four major compounds (D3G, D3R, C3G, and C3R) in BCE, produce phytoestrogen effects, which are favorable for the skin (Table 6).

A separate study was conducted to evaluate the effects of BCE on mRNA and protein expression of genes of Caco-2 cells, which are human epithelial colorectal adenocarcinoma cells (Kim et al., 2018). This study demonstrated that BCE increased low-density lipoprotein receptors without any changes to the cell mRNA. Overall, the data suggested that BCE increased the transport of cholesterol via the enterocytes, which suggests that the BCE play a part in the hypocholesterolemic effects (Kim et al., 2018). The exact mechanism of action was not determined in this study, which means that further *in vivo* studies are needed to characterize the mechanisms.

In addition to being able to affect cholesterol levels positively, BC have been reported to lower blood glucose levels and ameliorate glucose tolerance in both mice and rats, and also to decrease postprandial blood glucose concentrations in humans (Iizuka, Ozeki, Tani, & Tsuda, 2018). A recent study reported that dietary forms of BCE, which are heavily concentrated with delphinidin 3-rutinoside (D3R), can significantly reduce blood glucose levels and improve glucose tolerance in type 2 diabetic mice (Iizuka et al., 2018). The mechanistic changes that produced these effects were due to an increased secretion of glucagon-like peptide-1 (GLP-1) in plasma. It was also due to the upregulation of intestinal prohormone convertase 1/3 (PC1/3) expression and the activation of adenosine monophosphate-activated protein kinase-mediated translocation of the insulin-regulated glucose transporter (Glut4) in the skeletal muscle of type 2 diabetic mice (Iizuka et al., 2018).

A significant decrease in mean arterial pressure and total peripheral resistance in 15 endurance-trained male cyclists who received 600 and 900 mg BCE supplement per day during 2 h of prolonged exercise has been observed (Cook, Myers, Gault, Edwards, & Willems, 2017b; Table 6). In a separate study, the mean fat oxidation in endurance-trained females increased by 27% during 120 min of moderate-intensity cycling when ingested 600 mg/day of BCE in comparison to placebo (Strauss, Willems, & Shepherd, 2018). The time of consumption and the concentration of ANC from BC were important to enhance their health benefits associated to regular exercise (Lyall et al., 2009). It was also found that drinking 16 oz of BC nectar (BCN) twice a day for eight consecutive days at 48 h postexercise increased Oxygen Radical Absorbance Capacity (ORAC) blood levels in comparison to the placebo (BCN = 2.68% compared with PLA = –6.02%, P = 0.039). It was demonstrated that BCN consumption prior to and after a bout of eccentric exercise attenuated muscle damage and inflammation (Hutchison, Flieller, Dillon, & Leverett, 2016). Perkins, Vine, Blacker, and Willems (2015) tested New Zealand BCE (CurraNZ) on high-intensity intermittent running and postrunning lactate responses. They found that CurraNZ may enhance performance in sports characterized by high-intensity intermittent exercise as greater distances were covered with repeated sprints. There are human intervention studies that give evidence of the improvements to cognitive performance, modulation of blood flow, regulation of blood glucose, and inhibition of enzymes related to normal cognitive function after consuming BC (Watson et al., 2015; Watson, Okello et al., 2018; Watson, Scheepens et al., 2018).

Summary and Perspectives

There is an increased interest in BC in the United States because of their unique flavor and biological characteristics (Table 7). Various reports have concluded that there are four major ANC present in BC (rutinoside and glucoside forms of delphinidin and cyanidin) while other ANC may be present in much smaller concentrations. Further evaluations are needed to examine and document the differences in bioactive compounds in all known cultivars and varieties of BC. The characteristic bitter and astringent flavors in BC can be attributed to PAC with the intensity of the taste being determined by the mean degree of polymerization of the compounds. Although PAC are known to promote health, more research is needed to understand how to overcome the challenges that astringency and bitterness present for the formulation of desirable food products without the addition of sugar. Furthermore, it is equally important that the solution to this issue does not negate the health benefits of these complex compounds. It is not only the berries that have industrial uses, but also the pomace from which extractions can be made to produce natural pigments to be used as food additives and nutritional supplements. These products are in demand by consumers and can also minimize environmental impacts. Extractions of ANC and other bioactive compounds yield significant concentrations depending on the method, and there is a need to develop additional green and food safe methods for BC. Drying methods, particularly freeze-drying and convection drying, significantly reduce the concentration of phenolics in BC. This also presents a gap in knowledge, which needs to be addressed to preserve the beneficial aspects of these healthful fruits. Current research has demonstrated that BC have great potential to improve overall health particularly with diseases associated with inflammation and regulation of blood glucose. BC also have the potential to improve the performance and recovery times of athletes and also offer treatments for ophthalmological diseases such as glaucoma. Additionally, the use of BC in the cosmetics industry is also attractive due to their ability to activate estradiol pathways and decrease the appearance of wrinkles on the skin. Concentrations of ANC and other bioactive compounds are dependent on the genetics and growing conditions of the berries. However, the berries do exhibit much higher levels of phenolic compounds when grown in cooler climates. More research is needed to fully understand the breadth of health benefits to be gained from BC and how these berries can be incorporated into foods.

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Author Contributions

Cortez and Gonzalez de Mejia conceived the idea and drafted the structure of the review. Cortez compiled the information and wrote the first draft. Gonzalez de Mejia contributed with editing the manuscript, critical interpretation, and scientific guidance throughout the development of the manuscript. Both authors read and approved the final version.

Conflict of Interest

The authors declare no conflict of interest.

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