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A Review of the Nutritional Profile, Chemical Composition and Potential Health Benefits of *Aronia melanocarpa* (Chokeberry) Berries and Products

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ABSTRACT

Aronia melnocarpa, commonly known as chokeberry, originates from the eastern region of North America and belongs to the *Rosaceae* family within the *Maloideae* subfamily. The sour taste of fresh chokeberries makes them infrequently eaten as is, but they find extensive use in the food industry for creating fruit juices, fruit teas, wines, jams, jellies, and dietary supplements. Chokeberries represent a source of a wide range of bioactive compounds with potential health benefits for humans. Among the effects supporting human health are antidiabetic, anti-inflammatory, antimicrobial, and anticancer properties, as well as protection for the heart, liver, and nervous system. The abundant presence of polyphenols, such as phenolic acids, flavonols, anthocyanins, flavanols, and proanthocyanidins, plays a crucial role in conferring the remarkable bioactivity of chokeberries. These compounds are responsible for many of the health benefits associated with the consumption of chokeberries. Chokeberry fruits and their derived products showcase notable antioxidant properties and have the potential to promote health by effectively reducing the formation of free radicals. In this review, a comprehensive analysis of scientific research has been conducted to explore the polyphenolic compounds found in chokeberries, as well as their antioxidant potential. The findings in this review are likely to have a significant impact on future research focused on developing functional food products based on chokeberries. Chokeberries possess the potential to serve as food constituents intentionally crafted to augment antioxidant capacity. However, similar to other natural plants and medicinal products, conducting extensive research is crucial to assess the antioxidant potential, safety, and mechanisms of action of chokeberries. Therefore, the aim is to make a positive contribution to the continuation of research on the positive effects of chokeberry on health.

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Introduction

Aronia (chokeberry) is a member of the Maloideae subfamily within the Rosaceae family. Its origin can be traced back to the eastern regions of North America, and it comprises two species: *Aronia melanocarpa* (Michx.) Elliot (black) and *A. arbutifolia* (red). *A. prunifolia* (purple) is a third species that is a hybrid of the other two (Kulling and Rawel, 2008). Out of these three options, black chokeberry stands out as the most valuable and beneficial as a food source (Ćujić et al., 2018). This species prefers sunny and well-lit areas but can tolerate partial shade and short periods of drought. Black chokeberries have a limited tolerance to excessive soil moisture, which necessitates the implementation of drip irrigation during hot and dry periods (Negreanu-Pirjol et al., 2023).

Because of its cold-hardiness, *Aronia* can be grown not only in temperate climates but also in regions with temperatures as low as below -35°C (Ćujić et al., 2018). *Aronia* plants do not have specific requirements concerning climatic and ecopedological factors, and they are not prone to severe disease or pest attacks (Negreanu-Pirjol et al., 2023). Their adaptability to conditions unsuitable for other fruits makes them a common choice for ornamental purposes in gardens (Ćujić et al., 2018). *Aronia* was highly valued by Native Americans and was traditionally used to make tea for treating colds (Kulling and Rawel, 2008). Currently, *Aronia* is predominantly cultivated and utilized for the production of various products, including fruit juices, jams, liqueurs, wines, and food colorants. Consistent intake of antioxidant-rich vegetables, fruits and other food items is widely recognized to enhance overall health and is linked to a reduced risk of various chronic diseases. The beneficial health effects of plant-based foods primarily stem from the presence of bioactive compounds within them. Phytochemicals, commonly found in these plant-based foods, can exert protective effects against the onset of diverse diseases, either individually or through collaborative interactions known as synergistic effects (Ćujić et al., 2018).

The fruit and leaves of *A. melanocarpa* contain a significant abundance of diverse bioactive compounds, with a primary focus on polyphenolic compounds, along with vitamins and minerals. As a consequence, *Aronia* demonstrates a broad spectrum of beneficial health effects (Szopa et al., 2017; Jurikova et al., 2017).

Around 25% of the polyphenolic content in *Aronia* fruits consists of anthocyanins, with cyanidin derivatives being the most prevalent among them. The principal flavonol found in *A. melanocarpa* is quercetin. Essential constituents of *A. melanocarpa* encompass chlorogenic and neochlorogenic acids, alongside tannins. All these factors contribute to *Aronia* surpassing known antioxidant sources such as grapes, cranberries, blueberries, elderberries, or currants (Negreanu-Pirjol et al., 2023). The polyphenolic compounds in *A. melanocarpa* exhibit not only high antioxidant capacities but also antimicrobial, anti-inflammatory, antiviral, anticancer, and antidiabetic properties (Borowska et al., 2016; Kokotkiewicz et al., 2010; Kulling and Rawel, 2008; Jurikova et al., 2017; Szopa et al., 2017).

Aronia stands out among plant-based foods due to its high polyphenol content and potential health effects. The purpose of this study is to review the chemical composition and nutritional profile of *A. melanocarpa* fruits, fruit juice and pomace, providing essential information for the development of beneficial components and emphasizing their advantageous health properties.

Aronia's Nutritional Composition and Health-Beneficial Components

The chemical makeup of chokeberry fruit is influenced by several factors, including soil composition, climate conditions, grain maturity, storage conditions and harvesting techniques. It contains numerous compounds, including organic acids, carbohydrates, amino acids, minerals, polyphenols, vitamins and aroma compounds (Tolić et al., 2017; Kulling and Rawel, 2008).

Dark-colored fruits are widely acknowledged as significant providers of anthocyanins. Chokeberry, like other dark-colored fruits, is an essential reservoir of anthocyanins. *Aronia* is rich in health-beneficial compounds classified as antioxidants, including proanthocyanidins, flavonols, anthocyanins, flavanols and phenolic acids, which contribute to its status as a biologically active and polyphenol-rich source (Pliszka et al., 2008; Du et al., 2004; Ding et al., 2006; Zhang et al., 2021). Besides their antioxidant activity, polyphenols also play roles as carriers of characteristic taste, aroma, color, and nutritional value (Robards et al., 1999).

Table 1. Chemical composition of Aronia berries, juice and pomace.

	Berries	Juice	Pomace
pH	3.36–3.79 [Tanaka et al. 2001], 3.3–3.7 [Lancrajan et al. 2012], 3.23–3.57 [Skrede et al. 2012]	3.77–3.96 [Tolić et al. 2017], 3.54–3.92 [Tolić et al. 2015], 3.5 [Handeland et al. 2014], 3.42–3.72 [Sosnowska et al. 2016], 3.15–3.45 [Bolling et al. 2015], 3.5 [Daskalova et al. 2015]	
Titratable acidity	0.75–1.05 g/100 g [Ochmian et al. 2012], 1.42 g/100 g [Ochmian et al. 2009], 0.493–0.548 g/100 g [Skupień et al. 2007], 6.7–11.9 g/kg [Šnebergrová et al. 2014], 1.9–2.6 g/kg [Wichrowska et al. 2007], 1.03–1.44 g/100 g [Skrede et al. 2012], 1.24–1.31 g/100 g [Skupień et al. 2008]	0.89–1.06% [Tolić et al. 2017], 0.29–1.32% [Tolić et al. 2015], 0.85–1.22% [Bolling et al. 2015], 0.89% [Daskalova et al. 2015]	0.52–0.58% [Sójka et al. 2013]
Dry matter	15.30–19.50% [Ochmian et al. 2012], 17.9–26% [Mayer-Miebach et al. 2012], 26.67–30.76% [Skupień et al. 2007], 15.7% [Lancrajan et al. 2012], 22.14–23.45% [Wichrowska et al. 2007], 21.0–26.0% [Andrzejewska et al. 2015], 18.3–23.5 g/100 g [Skrede et al. 2012], 18.92–20.14% [Skupień et al. 2008], 15–31 [Skupień et al. 2007; Ochmian et al. 2012]	11–17 [Mayer-Miebach et al. 2012], 19.22–26.94% [Tolić et al. 2017], 11.1–17.4% [Mayer-Miebach et al. 2012], 15.46–16.87% [Oszmiański et al. 2016], 13.42–21.54% [Tolić et al. 2015], 18.1% [Daskalova et al. 2015]	45–50% [Mayer-Miebach et al. 2012], 90.21% [Pieszka et al. 2015], 93.6–94.9% [Sójka et al. 2013], 90.8% [Nawirska et al. 2004]
Dietary fiber	56 g/kg [Kulling et al. 2008]	0.3 g/100g [Yamane et al. 2017; Yamane et al. 2016]	21.79% [Pieszka et al. 2015], 63.5–77.9% [Sójka et al. 2013], 72.0% [Wawer et al. 2006]
Fat	0.09–0.17 g/100g [Tanaka et al. 2001] 0.14 g/100 g [Kulling et al. 2008]	<1 g/L [Yamane et al. 2017]	5.15% [Pieszka et al. 2015], 2.9–13.9% [Boncheva et al. 2013]
Protein	3.71 g/100 g [Cěrvenka 2011], 0.60–0.81 g/100g [Tanaka et al. 2001], 0.7 g/100g [Lancrajan 2012]	2 g/L [Yamane et al. 2017]	%4.9–24.1 [Sójka et al. 2013], 10.77% [Pieszka et al. 2015]
Total Sugar	9.16–13.79 g/100 g [Ochmian et al. 2012], 68–158 g/kg [Mayer-Miebach et al. 2012], 19.32–20.92 g/100 g [Skupień et al. 2007], 83.0–111.6 g/kg [Wichrowska et al. 2007], 6.21–6.91 g/100 g [Skupień et al. 2008]	89.49–162.37 g/L [Sosnowska et al. 2016], 12.0–19.6 g/100 mL [Handeland et al. 2014], 110–143 g/L [Mayer-Miebach et al. 2012]	84 g/kg [Mayer-Miebach et al. 2012]

Dietary fiber

Dietary fibers are essential compounds found in foods. They have the potential to bind harmful substances and heavy metals in the body, thereby reducing their levels (Nawirska et al., 2005). The consumption of high glycemic index foods is thought to play a substantial role in the emergence of various metabolic disorders. (Hauner et al., 2012). High intake of dietary fiber (DF) can help mitigate these risks (Stephen et al., 2017; Lovegrove et al., 2017).

A. melanocarpa fruits contain 56 g/kg or 5.6 g/100 g FW (fresh weight) of dietary fiber (Kulling and Rawel, 2008), while the fiber content in *Aronia* pomace varies between 21.79% and 77.9% DM (dry matter) (Pieszka et al. 2015; Sójka et al. 2013; Wawer et al. 2006). Data presented by Sójka et al. (2013) indicate that chokeberry pomace is characterized by significant cellulose (35%), hemicellulose (34%), lignin (24%), and pectin (8%) content. Rich in dietary fiber, *A. melanocarpa* by-products are considered valuable sources for food supplements and functional foods (Wawer et al., 2006).

Fat

According to research, *Aronia* fruits have a total fat content of 0.09–0.17 g/100g (Tanaka et al., 2001; Kulling and Rawel, 2008). The fat content in *Aronia* pomace ranges from 2.9% to 13.9% DM (Pieszka et al., 2015; Sójka et al., 2013). Studies have shown that the fat obtained from *A. melanocarpa* and its seeds is rich in tocopherols, sterols, and phospholipids. The dried pulp and seeds exhibit a fatty acid combination with a substantial presence of polyunsaturated fatty acids, with linoleic acid being the primary fatty acid, constituting approximately 73.6% of the total fatty acids (Zlatanov et al., 1999; Pieszka et al., 2015).

Protein

The protein content in *Aronia* fruits is generally low and falls within the range of 0.60–3.71 g/100g (Červenka et al., 2011; Tanaka et al., 2001; Lancrajan et al., 2012). Regarding pulp and dried pulp, the reported total protein content ranged from 4.9% to 24.1% and was found to be 10.77%, respectively. The most abundant amino acids in dried pulp were aspartic acid, arginine, and glutamic acid (Pieszka et al., 2015). In addition, research has shown that the fraction without seeds of the pulp has a considerably lower protein content when compared to the seed fraction (Sójka et al., 2013; Pieszka et al., 2015).

Sugar

Several studies conducted by different researchers have reported that the total sugar content in *Aronia* fruits falls within a range of 6.21 to 20.92 g per 100 grams (Ochmian et al., 2012; Mayer-Miebach et al., 2012; Skupień et al., 2007; Wichrowska et al., 2007; Skupień et al., 2008). In *Aronia* juice, the total sugar content has been found to be between 8.94 and 19.6 g/100 mL (Sosnowska et al., 2016; Handeland et al., 2014; Mayer-Miebach et al., 2012). For *Aronia* pomace, a sugar content of 84 g/kg was reported (Mayer-Miebach et al., 2012).

Minerals

Minerals and trace elements hold a crucial role in cell metabolism and are instrumental in activating enzymes that participate in antioxidant systems (Skupień et al., 2008). High intake of potassium (K), calcium (Ca), magnesium (Mg) and has been associated with reduced risk of osteoporosis, stroke, and hypertension (Oszmiański and Lachowicz, 2016). Iron and other trace minerals are fundamental constituents of various compounds responsible for oxygen transport and storage systems in the body. Moreover, they act as cofactors for enzymes, facilitating their proper functioning (Oszmiański and Lachowicz, 2016; Tolić et al., 2015; Daskalova et al., 2015). Molybdenum (Mo), as a micro-nutrient, serves as a structural component of xanthine dehydrogenase and xanthine oxidase enzymes. These enzymes have a significant function in the urea synthesis pathway (Jakobek et al., 2012a).

Based on previous research, Table 2 presents the micro and macro element contents in fresh chokeberry fruit, pomace and juice. The dominant macro elements reported by the authors are potassium and calcium, while phosphorus and magnesium are other elements showing relatively high concentrations. Macro elements play a crucial role in the control and regulation of metabolism. Also, micro-elements have essential biological functions as integral constituents of enzymes or protein structures. They are involved in various essential functions, including oxygen storage, electron transport, metal transport, redox processes, and a wide range of biochemical reactions (Romani et al., 2016). Regarding micro elements in *Aronia* and its products, the highest values were found for iron (Fe) and manganese (Mn).

Polyphenols

Blackberries, whole grains, a variety of vegetables, grapes and numerous other fruits are abundant sources of polyphenols, being classified chemically as polyphenolic compounds. (Zhang et al., 2021). Polyphenols encompass various subgroups of phenolic compounds with multiple hydroxyl groups and aromatic rings (Kähkönen et al., 2001; Manach et al., 2004). Polyphenols are widely recognized as one of the most significant antioxidants present in the human diet. Chokeberry fruits stand out as a highly abundant source of polyphenols, encompassing flavanols, flavonols, anthocyanins, phenolic acids, and proanthocyanidins. (Oszmiański and Lachowicz, 2016; Denev et al., 2013; Dudonné et al., 2015; Gramza-Michałowska et al., 2017). The presence of phenolic compounds in fruits is influenced not only by the plant variety but also by cultivation conditions, including factors like soil nutrient content, light exposure, temperature, water availability, and the timing of harvesting. According to researchers, the composition of polyphenols in chokeberry experiences significant modifications as the fruit development and ripens, with the greatest total polyphenol content observed in unripe fruits (Gralec et al., 2019). Polyphenols are the key bioactive components responsible for the high bioactivity exhibited by chokeberry. (Sidor and Gramza-Michałowska, 2019). It is challenging to recommend precise dosages of polyphenols to be consumed through foods (Williamson, 2017). On average, the daily intake of phenolics is estimated to be 1 g (Malik et al., 2003). The total polyphenol content determined by researchers in *Aronia* fruit, *Aronia* juice, and pomace is presented in Table 3. The polyphenol content in *Aronia* fruit was found to vary within the range of 6.03-23.40 g/kg, while in *Aronia* juice, it ranged from 2.73 to 11.24 g/L.

Table 2. Mineral composition of Aronia berries, juice and pomace

Mineral	Berries	Juice	Pomace
Ca	60–117 mg/100 g [Pavlovic et al. 2015]; 22.8–43.9 mg/100 g [Tanaka et al. 2001], 32.2 mg/100 g [Lancrajan et al. 2012], 119.0–552.3 mg/kg [Šnebergrová et al. 2014]	14–123 mg/100 g [Pavlovic et al. 2015]; 150.4 mg/L [Cindrić et al. 2017]; 138–1225 mg/kg [Pavlovic et al. 2015], 151 ppm [Handeland et al. 2014]	219–408 mg/100 g [Pavlovic et al. 2015]; 2.75 g/kg [Pieszka et al. 2015]
Mg	15.5–17.4 mg/100 g [Tanaka et al. 2001], 16.2 mg% [Lancrajan et al. 2012], 83.3–314.2 mg/kg [Šnebergrová et al. 2014], 164–578 mg/kg [Pavlovic et al. 2015]	140 mg/L [Cindrić et al. 2017]; 209–589 mg/kg [Pavlovic et al. 2015], 85 ppm [Handeland et al. 2014]	37–250 mg/100 g [Pavlovic et al. 2015]; 0.88 g/kg [Pieszka et al. 2015]
K	164–265 mg/100 g [Tanaka et al. 2001], 218 mg% [Lancrajan et al. 2012], 1356.3–3659.7 mg/kg [Šnebergrová et al. 2014], 2707–4977 mg/kg [Pavlovic et al. 2015]	5.3 mg/L [Cindrić et al. 2017]; 848–3204 mg/kg [Pavlovic et al. 2015], 1242 ppm [Handeland et al. 2014]	181–308 mg/100 g [Pavlovic et al. 2015]; 2.78 g/kg [Pieszka et al. 2015]
Na	2.0–3.7 mg/100 g [Tanaka et al. 2001], 2.6% [Lancrajan et al. 2012], 12.5–16.8 mg/kg [Pavlovic et al. 2015]	6.4 mg/L [Cindrić et al. 2017]; 19.6–56.3 mg/kg [Pavlovic et al. 2015], 19 ppm [Handeland et al. 2014]	5–9 mg/100 g [Pavlovic et al. 2015], 0.037 g/kg [Pieszka et al. 2015]
P	15.9–21.7 mg/100 g [Tanaka et al. 2001], 257.0–417.5 mg/kg [Šnebergrová et al. 2014], 239–956 mg/kg [Pavlovic et al. 2015]	167–1037 mg/kg [Pavlovic et al. 2015]	239 mg/100 g [Pavlovic et al. 2015]; 2.39 g/kg [Pieszka et al. 2015]
Se	0.21–0.28 mg/kg [Pavlovic et al. 2015]	0.07–0.1 mg/100 g [Pavlovic et al. 2015]	
Cu	0.035–0.056 mg/100 g [Tanaka et al. 2001], 0.82–2.11 mg/kg [Pavlovic et al. 2015]	0.68–4.51 mg/kg [Pavlovic et al. 2015]	0.5–1.2 mg/100 g [Sójka et al. 2013]; 1.95 mg/kg [Pieszka et al. 2015]
Fe	0.33–1.68 mg/100 g [Tanaka et al. 2001], 9.4–14.2 mg/kg [Pavlovic et al. 2015]	7.2–25.2 mg/kg [Pavlovic et al. 2015]	7.5–8.6 (mg/100 g) [Sójka et al. 2013]; 197 mg/kg [Pieszka et al. 2015]
Zn	0.090–0.220 mg/100 g [Tanaka et al. 2001], 4.09–8.40 mg/kg [Pavlovic et al. 2015]	0.89–3.45 mg/kg [Pavlovic et al. 2015]	0.6–3.7 mg/100 g [Pavlovic et al. 2015]; 15.7 mg/kg [Pieszka et al. 2015]
Mn	0.132–0.263 mg/100 g [Tanaka et al. 2001], 5.49–17.89 mg/kg [Pavlovic et al. 2015]	2.98–11.77 mg/kg [Pavlovic et al. 2015]	3.2 mg/100 g [Sójka et al. 2013]; 31.5 mg/kg [Pieszka et al. 2015]
Si	2.37–6.37 mg/kg [Pavlovic et al. 2015]	0.3–0.7 mg/100 g [Pavlovic et al. 2015]	
Cr	0.49–0.53 mg/kg [Pavlovic et al. 2015]	0.55–0.74 mg/kg [Pavlovic et al. 2015]	
Mo	0.016–0.021 mg/kg [Pavlovic et al. 2015]	0.005–0.006 mg/100 g [Pavlovic et al. 2015]	
Ni	0.143–0.740 mg/kg [Pavlovic et al. 2015]	0.130–0.860 mg/kg [Pavlovic et al. 2015]	
Pb	0.048–0.091 mg/kg [Pavlovic et al. 2015]	0.006–0.01 mg/100 g [Pavlovic et al. 2015]	
Cd	0.016–0.041 mg/kg [Pavlovic et al. 2015]	0.050–0.064 mg/kg [Pavlovic et al. 2015]	

Flavonoids and Phenolic Acids

Flavonoids are polyphenolic compounds that contain two aromatic rings linked together by a three-carbon bridge, known as C6-C3-C6 (Zhang et al., 2021). Flavonoids are divided into various subclasses, each highlighting important chemical properties. *A. melanocarpa* fruits are abundant in compounds like proanthocyanidins, phenolic acids, and anthocyanidins. However, it is noteworthy that they have a notably low level of flavonols. (Negreanu-Pirjol et al., 2023). Numerous studies have demonstrated that chokeberries possess a relatively low flavonol content, comprising approximately 1.3% of the total polyphenols. Anthocyanins, on the other hand, are one of the most significant phenolic compound groups found in black chokeberries (Sidor et al., 2019). These compounds are members of the flavonoid family but are characterized by their unique capability to form flavilium cations (Riaz et al., 2016). Anthocyanins in Aronia account for approximately 25% of the total polyphenol content (Jurendić and Ščetar, 2021).

Primarily, four distinct cyanidin glycosides stand out among anthocyanins: 3-O-glucoside (1.3%), 3-O-galactoside (68.9%), 3-O-xyloside (2.3%) and 3-O-arabinoside (27.5%) (Jurendić and Ščetar, 2021). Additionally, minute quantities of pelargonidin arabinoside and pelargonidin 3-O-galactoside have been identified (Oszmiański and Wojdylo, 2005). Chokeberry stands out as one of the most abundant plant sources of anthocyanins. The distinct colors of many vegetables and fruits originate from these compounds (de Pascual-Teresa et al., 2010; Minkiewicz et al., 2004; Malien-Aubert et al., 2001). Additionally, as the fruit ripens, the higher concentration of anthocyanins contributes to the enhancement of its color and visual attractiveness (Gralec et al., 2019). Environmental conditions impact the stability of anthocyanins, and consequently, their levels may decrease following sudden changes (Negreanu-Pirjol et al., 2023). The processing of fruits may significantly reduce the total anthocyanin content (Williamson, 2017). It has been observed that storing *A. melanocarpa* fruits at 70°C for 24 hours can lead to a 50% reduction in anthocyanin content (Liang et al., 2021). Phenolic acids constitute approximately 7.5% of the total polyphenolic compounds in *A. melanocarpa* extracts, where chlorogenic acid and neochlorogenic acid are the primary constituents (Oszmiański and Wojdylo, 2005). Chlorogenic acid, the principal phenolic acid, is derived from caffeic acid through an ester bond with quinic acid (Jurikova et al., 2017). Furthermore, research indicates that approximately 40% of chokeberry's antioxidant activity can be attributed to proanthocyanidins (Denev et al., 2019).

Table 3. Phenolic compounds of Aronia berries, juice and pomace

Berries	Juice	Pomace
Polyphenols (total)		
1845–2340 mg GAE/100 g [Ochmian et al. 2012], 7.78–12.85 g GAE/kg [Rop et al. 2010], 13.3 g GAE/kg [Kapci et al. 2013], 15.0–17.9 g CE/kg [Mayer-Miebach et al. 2012], 603 mg GAE/100 g [Dudonné et al. 2015], 1079–1921 mg GAE/100 g [Wangensteen et al. 2014], 1540.01 mg GAE/100 g [Najda et al. 2013], 10637.20 mg GAE/kg; [Jakobek et al. 2007], 8563.8–12055.7 mg GAE/kg [Jakobek et al. 2012b]	11.24 g/L [Daskalova et al. 2019], 7.77–11.24 g/L [Valcheva-Kuzmanova et al. 2019], 8834–11093 mg GAE/L [Tolić et al. 2017], 3002–6639 mg GAE/L [Tolić et al. 2015], 675–755 mg /100 mL GAE [Handeland et al. 2014], 2.73–10.35 g /L GAE [Sosnowska et al. 2016], 4772.2 mg GAE/L [Daskalova et al. 2015], 4.00 g /L GAE [Pozderović et al. 2016; Popović et al. 2016], 6484 mg GAE/L [Tomić et al. 2016], 709.3 mg GAE/100 mL [Valcheva-Kuzmanova et al. 2013a], 6652 mg /L GAE [Valcheva-Kuzmanova et al. 2013b], 5461 mg GAE/L [Sainova et al. 2012], 3172–7340 mg, GAE/L [Borowska et al. 2009]	63.1 g GAE/kg [Kapci et al. 2013], 31–63 g CE/kg [Mayer-Miebach et al. 2012]
Phenolic acids		
121.9 mg/100 g [Ochmian et al. 2009], 63.9 mg/100 g [Dudonné et al. 2015], 77–96 mg/100 g [Mattila et al. 2006]		
Hydroxycinnamic acids		
1.4–1.5 g /kg ChAE [Mayer-Miebach et al. 2012], 116.4 mg /100 g ChAE [Wilkes et al. 2014], 739.3–1670.3 mg /kg ChAE [Jakobek et al. 2012b]	0.45–0.59 g /kg ChAE [Mayer-Miebach et al. 2012], 48.9–77.9 mg /100 g ChAE [Wilkes et al. 2014]	0.72–0.82 g ChAE/kg [Mayer-Miebach et al. 2012], 89.7–231.6 mg /100 g ChAE [Sójkaal et al. 2013]
Anthocyanins (Total)		
256.4 mg/100 g [Vagiri et al. 2017], 6.2–6.7 g /kg CGlE [Mayer-Miebach et al. 2012], 529.3 mg/100 g [Ochmian et al. 2009], 357 mg CGlE/100 g [Dudonné et al. 2015], 249–447 mg /100 g CGaE [Wangensteen et al. 2014], 1480.0 mg CGlE/kg [Wu et al. 2004], 619.2 mg /100 g CGlE [Wilkes et al. 2014], 4056.22 mg CGlE/kg [Jakobek et al. 2007], 1500.9–5486.2 mg /kg CGlE [Jakobek et al. 2012b], 4.5 g CGlE/kg [Kapci et al. 2013], 498.98 mg/100 g [Najda et al. 2013]	0.86–2.13 g/L [Valcheva-Kuzmanova et al. 2019], 2.8–45.2 mg /100 mL CgaE, [Handeland et al. 2014], 4.76 g/L [Wilkowska et al. 2017], 221.4 mg/L [Sainova et al. 2012], 19.10 mg/100 mL [Wiczkowski et al. 2010], 1829–2768 mg CGlE/l [Tolić et al. 2017], 0.10–0.67 g CGlE/l [Sosnowska et al. 2016], 369.47 mg CGlE/l [Popović et al. 2016; Pozderović et al. 2016], 106.8 mg /100 mL CGlE [Valcheva-Kuzmanova et al. 2013a], 508–1087 mg /l CGaE [Borowska et al. 2009], 59.3–1118 mg /l CGlE [Vlachojannis et al. 2015]	738.7–1221.1, mg/100 g [Vagiri et al. 2017], 11.9–19.5 g /kg CGlE [Mayer-Miebach et al. 2012], 10 g CGlE/kg [Kapci et al. 2013]
Cyanidin-3-O-galactoside		
417–636 mg/100 g [Skupień et al. 2007; Gralec et al. 2019; Ochmian et al. 2012], 1010.80-1203.56 mg/kg [Rop et al. 2010], 2917.2 mg CGIE/kg [Kapci et al. 2013], 4.1-4.4 g CGIE/kg [Mayer-Miebach et al. 2012], 379.36 mg/100g [Ochmian et al. 2009], 229 mg CGIE/100g [Dudonné et al. 2015], 989.7 mg CGIE/100 g [Wu et al. 2004], 1243 mg CGIE/100g [Tarko et al. 2009], 2794.74 mg CGIE/kg [Jakobek et al. 2007], 1055.3-3621.0 mg CGIE/kg [Jakobek et al. 2012b]	7.87 g/L [Oszmiański et al. 2005], 1.49 g/L [Daskalova et al. 2019], 0.64–14.98 g/L [Valcheva-Kuzmanova et al. 2019], 46.58–96.88 CGlE mg/L [Sosnowska et al. 2016], 301 mg CArE/l [Tomić et al. 2016], 3.16 g/L [Wilkowska et al. 2017], 44.0–822.1 mg CGlE/l [Vlachojannis et al. 2015], 107.6 mg/100 g [Kardum et al. 2014c], 20.0 mg/L [Valcheva-Kuzmanova et al. 2013b], 143.7 mg/L [Sainova et al. 2012]	1120 mg/100 g [Oszmiański et al. 2005], 4600.5 mg CGlE/kg [Kapci et al. 2013], 7.6–12.5 g CGlE/kg [Mayer-Miebach et al. 2012], 437.2–754.6 mg/100 g [Vagiri et al. 2017]
Cyanidin-3-O-glucoside		
8–27 mg/100 g [Skupień et al. 2007; Gralec et al. 2019; Ochmian et al. 2012], 7.11 mg/100 g [Ochmian et al. 2009], 127 mg/kg [Kapci et al. 2013], 18.15-21.15 mg/100 g [Kader et al. 2005], 37.6 mg/100 g [Wu et al. 2004], 200.0 mg/kg [Veberic et al. 2015]	28 mg/100 g [Oszmiański et al. 2005], 0.12 g/L [Daskalova et al. 2019], 0.04–0.12 g/L [Valcheva-Kuzmanova et al. 2019], 0.3–2.0 mg CGaE/100 mL [Handeland et al. 2014], 0.16 g/L [Wilkowska et al. 2017], 4.9 mg/100 g [Kardum et al. 2014c], 4.4 mg/L [Valcheva-Kuzmanova et al. 2013a], 2.01-4.37 mg/L [Sosnowska et al. 2016], 3.7-5.7 mg/L [Bursać Kovačević et al. 2016], 9.28 mg/L [Popović et al. 2016; Pozderović et al. 2016], 21 mg/L [Tomić et al. 2016], 2.4-41.9 mg/L [Vlachojannis et al. 2015]	79 mg/100 g [Oszmiański et al. 2005], 237.7 mg/kg [Kapci et al. 2013], 33.9-52.0 mg/100 g [Vagiri et al. 2017], 0.24-0.44 g/kg [Mayer-Miebach et al. 2012]
Cyanidin-3-O-arabinoside		
129–299 mg/100 g [Skupień et al. 2007; Gralec et al. 2019; Ochmian et al. 2012], 941.82–1553.29 mg/kg [Rop et al. 2010], 1359.4 mg CGlE/kg [Kapci et al. 2013], 1.9–2.1 g CGlE/kg [Mayer-Miebach et al. 2012], 116.39 mg/100 g [Ochmian et al. 2009], 112 mg CGlE/100 g [Dudonné et al. 2015], 52–149 mg CGaE/100 g [Wangensteen et al. 2014], 399.3 mg CGlE/100 g [Wu et al. 2004], 1243.2 mg CyE/kg [Veberic et al. 2015], 154.7 mg CGlE/100 g [Wilkes al. 2014], 146 mg CGaE/100 g [Slimestad et al. 2005], 544 mg CGlE/100 g [Tarko et al. 2009], 993.77 mg CGlE/kg [Jakobek et al. 2007], 367.2–1532.4 mg CGlE/kg [Jakobek et al. 2012b]	324 mg/100 g [Oszmiański et al. 2005], 0.50 g/L [Daskalova et al. 2019], 0.18 to 0.50 g/L [Valcheva-Kuzmanova et al. 2019];0.7–10.7 mg CGaE/100 mL [Handeland et al. 2014], 11.47–32.59 CGlE mg/L [Sosnowska et al. 2016], 78.47 mg/L [Popović et al. 2016; Pozderović et al. 2016], 1.44 g/L [Wilkowska et al. 2017], 11.3–249.9 mg CGlE/l [Vlachojannis et al. 2015], 36.2 mg/100 g [Kardum et al. 2014c], 8.2 mg/L [Valcheva-Kuzmanova et al. 2013b], 61.7 mg/L [Sainova et al. 2012], 110.1–178.7 mg /l CGaE [Borowska et al. 2009], 5.12 mg /100 mL CGaE [Krajka-Kuźniak et al. 2009]	533 mg/100 g [Oszmiański et al. 2005], 1651.1 mg CGIE/kg [Kapci et al. 2013], 3.7-5.7 g CGIE/kg [Mayer-Miebach et al. 2012], 217.5–366.7 mg/100 g [Vagiri et al. 2017]
Cyanidin-3-O-xyloside		
53 mg/100 g [Szopa et al. 2017; Oszmiański et al. 2005], 29–38 mg/100 g [Skupień et al. 2007; Gralec et al. 2019; Ochmian et al. 2012], 165.8 mg CGIE/kg [Kapci et al. 2013], 26.40 mg/100 [Ochmian et al. 2009], 8.12 mg/100 g CGlE [Dudonné et al. 2015], 51.5 mg/100 g CGlE [Wu et al. 2004], 38.7 mg CyE/kg [Veberic et al. 2015], 9.92 mg/100 g [Tian et al. 2017], 20.1 mg /100 g CGlE [Wilkes al. 2014], 10 mg CGaE/100 g [Slimestad et al. 2005], 73 mg CGlE/100 g [Tarko et al. 2009], 146.02 mg CGlE/kg [Jakobek et al. 2007], 44.3–233.1 mg CGlE/kg [Jakobek et al. 2012b]	0.34 g/L [Oszmiański et al. 2005], 4.6 mg/L [Daskalova et al. 2019], 1.24–4.74 mg/L CGlE [Sosnowska et al. 2016], 0.2–2.1 mg /100 mL CGaE [Handeland et al. 2014], 3.2–5.2 mg/L [Bursać Kovačević et al. 2016], 6.88 mg/L [Popović et al. 2016; Pozderović et al. 2016], 0.6 mg/L [Valcheva-Kuzmanova et al. 2013b], 11.6 mg/L [Sainova et al. 2012], 0.59 mg/100 mL [Wiczkowski et al. 2010], 19.8–29.4 mg CGaE/l [Borowska et al. 2009], 0.59 CGaE/100 mL [Krajka-Kuźniak et al. 2009]	105 Pomace mg/100 g [Oszmiański et al. 2005], 223.4 mg CGlE/kg [Kapci et al. 2013], 36.7–63.3 mg CGlE/100 g [Vagiri et al. 2017], 0.3–0.6 g /kg CGlE [Mayer-Miebach et al. 2012]
Procyanidins		
1646 mg/100 g [Ochmian et al. 2012; Gralec et al. 2019], 1426.66-1645.64 mg/100 g [Skupień et al. 2007], 663.7 mg/100 g [Wu et al. 2004], 868.6 mg CE/100 g [Wilkes et al. 2014]	15.79 g/L [Oszmiański et al. 2005], 60-72 CyE mg/100 mL [Handeland et al. 2014], 3529.1 mg CE/l [Oprea et al. 2014], 240 mg CE/l [Tomić et al. 2016], 34.2 mg CE/100 mL [Stanisavljević et al. 2015], 3122.5 mg/L [Sainova et al. 2012], 3926.2 mg/L [Valcheva-Kuzmanova et al. 2013b], 293.38 mg/100 mL [Krajka-Kuźniak et al. 2009]	8192 mg/100 g [Oszmiański et al. 2005], 24-129 g CE/kg [Hirth et al. 2015]

The Health Benefits of Chokeberry Fruits

Antioxidant Effects

Consistent intake of antioxidant-rich foods is recommended for improving overall health and reducing the risk of chronic diseases (Bal et al., 2023). Polyphenols are the primary constituents responsible for the antioxidant potential of plant-based foods, including fruits and vegetables (Ćujić et al., 2018). Polyphenols, numbering over 8000 known variants in the plant kingdom, rank as the most prevalent and crucial dietary antioxidants, significantly adding to the antioxidant potential of plant-based foods (Ćujić et al., 2018; Pavlovic et al., 2015).

Polyphenols exert antioxidant effects as a result of their redox potential. Here, acting as hydrogen donors and singlet oxygen quenchers, polyphenols have the ability to serve as reducing agents with the potential for metal-chelation. These attributes empower polyphenols to combat oxidative stress effectively, demonstrating strong safeguards against oxidative damage at the cellular level (Oszmiański and Wojdylo, 2005). Oxidative damage or oxidative stress occurs when there is an imbalance between radical formation and antioxidant defense (Ehlenfeldt et al., 2001; Moyer et al., 2002; Mohammed et al., 2023a). It is also a significant factor in the development of various diseases, such as Alzheimer's disease, stroke, heart disease, and Parkinson's disease (Denev et al., 2012; Mohammed et al., 2023b). A range of antioxidants alleviate oxidative stress and can delay or prevent the oxidation of specific substrates (Ehlenfeldt et al., 2001). Including dietary antioxidants as a component of a balanced diet is advised to bolster the body's antioxidant defenses and reduce the risk of cardiovascular and other chronic diseases (Arts and Hollman, 2005; Hooper et al., 2008; Uysal et al., 2023). Chokeberry is considered to be one of the most potent dietary antioxidants due to its substantial polyphenol content (Ćujić et al., 2018).

Previous research has shown that chokeberry has significantly higher antioxidant potential compared to other fruits, such as cranberries, blueberries, and black currants (Ehlenfeldt et al., 2001; Denev et al., 2012). Evaluating the overall phenolic content and antioxidant capacity of various fruits, chokeberry has been found to exhibit substantially higher total antioxidant capacity when compared to other fruits like cranberries, blueberries, and black currants. Black chokeberry boasts a wealth of polyphenols, vitamins C and E, and essential minerals like copper and zinc (Zhang et al., 2021). These constituents contribute to the heightened antioxidant capacity of chokeberry (Seeram et al., 2008). Chokeberry's antioxidant activity has also been demonstrated through *in vitro* studies. *In vitro* antioxidant activity of Aronia berries has been attributed to approximately 40% proanthocyanidins, followed by anthocyanins (24%), hydroxycinnamic acids (18%), and epicatechin (11%) (Jurendić and Ščetar, 2021).

The *in vivo* mechanisms of polyphenol antioxidant activity surpass radical scavenging and encompass functions such as reducing reactive nitrogen and oxygen species post-absorption, restoring antioxidant enzymes, inhibiting prooxidants, and modulating cellular signaling related to antioxidant levels and enzymes (Pavlovic et al., 2015; Tolić et al., 2015; Unal et al., 2022). For example, a study investigating the influence of chokeberry extract on oxidative stress in human plasma treated with homocysteine showed that the introduction of chokeberry extract led to a rise in overall antioxidant capacity (Malinowska et al., 2012). Kedzierska et al. (2012) showcased the suppressive effects of chokeberry extract on the generation of superoxide anion radicals in platelets collected from both breast cancer patients and healthy individuals. Chokeberry anthocyanin extract exhibited protective effects against hydrogen peroxide and high glucose-induced oxidative stress and cytotoxicity in pancreatic β-cells (βTC3) (Ćujić et al., 2018). Moreover, pre-treatment of pancreatic β-cells with chokeberry extract resulted in increased activity of antioxidant enzymes comparison to cells solely exposed to prooxidant agents (Rugină et al., 2015). In another study, the antioxidant activity was examined during a clinical trial involving 11 healthy volunteers who consumed 250 mL of Aronia fruit juice daily for three weeks. The participants' serum antioxidant capacity, tested using spectrophotometric methods with stable DPPH radical cations, showed a significant increase (Nowak et al., 2016). Black chokeberry juice has been found to have cardioprotective effects and can slow down atherosclerosis, as well as possessing anti-aging properties (Zhang et al., 2021). According to Pilaczynska-Szczesniak et al. (2005), rowers who consumed 150 mL of fruit juice daily during a one-month training camp experienced a decrease in oxidative damage to red blood cells induced by exercise. Green, unripe chokeberry fruits lack anthocyanins but exhibit high antioxidant activity due to their elevated proanthocyanidin and flavonoid content (Gralec et al., 2019). Results obtained by Szopa et al. (2017) demonstrated that leaves of Aronia species also exhibit robust antioxidant capacity, making them potentially interesting for therapeutic and dietary purposes. Additionally, apart from chokeberry fruits, fruit products, and post-production waste also demonstrate antioxidant potential (Sidor and Gramza-Michałowska, 2019). Nawirska et al. (2007) reported that chokeberry pomace showed moderate activity when compared to other pomaces. On the other hand based on Pieszka et al. (2015)'s findings, dried chokeberry pomace demonstrated superior antioxidant properties compared to apple, black currant, carrot pomaces, and strawberry. Najda and Łabuda (2013) conducted research on various fruits' antioxidant activity and observed that chokeberry fruits exhibited greater antioxidant activity compared to the other eight fruits. Analyzing the antiradical activity of fruit juice and pomace (fruit residue), Sidor and Gramza-Michałowska (2019) showed that pomace exhibited the highest activity, followed by fruit and fruit juice. In testing the antioxidant potential of fruit juices, chokeberry juice demonstrated the highest DPPH radical scavenging ability (72.44 mol TE/mL) (Jakobek et al., 2007). Keskin-Šašić et al. (2012) confirmed that Aronia juice demonstrated higher antiradical activity than 14 other fruit juices. Zheng and Wang (2003) evaluated the antioxidant activity of chokeberry in a study excluding proanthocyanidins and found that activity was mainly derived from anthocyanins

(53.1%), phenolic acids (38.2%), and flavonols (8.7%). Research on chokeberry products has revealed that the antioxidant potential of these products varies based on the harvest time and the year of the raw material (Tolić et al., 2017; Bolling et al., 2015). Another crucial factor affecting the antioxidant properties of Aronia products is the technological production processes (Sidor and Gramza-Michałowska, 2019).

Antioxidant compounds play a vital role in promoting human health by preventing damage to normal cells through their ability to counteract and inhibit free radicals. Their antioxidant effects are valuable in alleviating conditions caused by oxidative stress, such as cancer, infections, heart disease, and diabetes (Ren et al., 2022; Mohammed et al., 2022). In this context, the significant abundance of phenolic compounds and other natural substances exhibiting robust antioxidant activity in Aronia berries might contribute to enhancing human health (Sun et al., 2017).

Effects on Cardiovascular Health

One of the prevalent chronic conditions is cardiovascular disease, and its share in global mortality and morbidity is considerable. Metabolic disorders associated with oxidative stress, hypertension, and obesity are among the risk indicators for cardiovascular diseases. Epidemiological investigations carried out in both industrialized and developing nations have confirmed that hypertension contributes the most to the development of cardiovascular and related diseases (Catalán-Ramos et al., 2014; Mancia et al., 2007). Regular consumption of chokeberry and its products can mitigate numerous risk factors that trigger the onset of cardiovascular diseases.

In a study, Chokeberry juice led to a significant reduction in diastolic blood pressure after six weeks of regular intake in men with mild hypercholesterolemia (Skoczynska et al., 2007). A comprehensive analysis of controlled clinical trials indicated that daily supplementation with Aronia fruit extract for six to eight weeks significantly lowered systolic blood pressure and overall cholesterol levels, which are key factors in cardiovascular disease risk, in adult participants (Hawkins et al., 2021). In another clinical research study, 23 patients without pharmacologically treated grade I hypertension consumed 200 mL of phenolic-rich Aronia juice daily for four weeks, resulting in a significant decrease in average 24-hour, awake systolic and diastolic blood pressure. Additionally, triglyceride levels and total low-density lipoprotein cholesterol levels exhibited notable reductions after four weeks of Aronia juice consumption (Kardum et al., 2015).

The favorable impact of consuming Chokeberry juice and extract on blood pressure is likely attributed to the substantial presence of phenolic compounds within them. Polyphenols can influence hypertension and general cardiovascular well-being through their capacity to diminish oxidative stress within the blood vessels (Jurendić and Ščetar, 2021).

In a study involving 44 patients with a previous heart attack, a double-blind, placebo-controlled, parallel investigation was conducted, where black chokeberry extract was administered via injection, and its impacts were assessed. Participants who were administered the extract for a duration of 6 weeks exhibited notable reductions in LDL levels, inflammation, and oxidative stress in comparison to individuals solely consuming statin medications (Valcheva-Kuzmanova et al., 2005). Studies conducted on rats with induced hypertension showed that the treatment group treated with *Aronia melanocarpa* ethanolic extract exhibited lower blood pressure values compared to the control group. The decrease in blood pressure was emphasized to be associated with enhancement of overall antioxidant capacity and mitigation of lipid peroxidation (Ciocoiu et al., 2013). Both *in vivo* and *in vitro* tests indicate that phenolic compounds play a role in safeguarding and rejuvenating endothelial cells (Poreba et al., 2009) and have antiplatelet effects (Bijak et al., 2011; Olas et al., 2008). Given that oxidative stress might play a role in the development of cardiovascular diseases, it is suggested to consume dietary antioxidants such as polyphenols as a means of preventing them. Another significant health effect of polyphenols is their role in regulating lipid levels. Due to their antioxidant effects, polyphenols can protect lipids against oxidation in both food items and the body. This is particularly important for foods rich in unsaturated fatty acids that are prone to lipid peroxidation, since the byproducts of lipid peroxidation can enter the body and result in harm (Ćujić et al., 2018).

Polyphenols found in the gastrointestinal system can improve lipid oxidation levels and reduce the adverse effects of lipid peroxidation products (Görelik et al., 2013; Kanner et al., 2012). Additionally, certain polyphenolic compounds can impact the production of lipids in the liver and/or their processing in the intestines. Therefore, through a range of mechanisms, polyphenols sourced from foods like chokeberry can positively impact lipid levels (Ćujić et al., 2018). In a study, six weeks of chokeberry juice supplementation resulted in a significant decrease in levels of triglycerides, overall cholesterol, and LDL cholesterol among men with mild hypercholesterolemia (Poreba et al., 2009). Another study found that four weeks of chokeberry fruit juice consumption lowered triglyceride levels in individuals with high-normal blood pressure or grade I hypertension (Kardum et al., 2015). In another study, the intake of 300 mg of chokeberry extract daily for two months significantly reduced triglycerides, total cholesterol, and LDL cholesterol levels in subjects with metabolic syndrome (Broncel et al., 2010). Additionally, out of the 31 fruit extracts examined, chokeberry exhibited the highest efficacy in inhibiting pancreatic lipase activity. As pancreatic lipase plays a pivotal role in the assimilation of dietary triglycerides, these results imply that incorporating chokeberry fruits into the diet could serve as a strategy to diminish fat absorption (Sosnowska et al., 2015).

In a parallel and placebo-controlled study conducted by Stojković et al. (2021), the effects of daily consumption of Aronia juice for four weeks on peripheral blood leukocytes' nucleotide element-1 DNA methylation and plasma profiles of polyunsaturated fatty acids (PUFAs) were examined in individuals at risk for cardiovascular disease. The outcomes indicated that the ingestion of Aronia fruit led to a decrease in LINE-1 methylation levels and the ratio of arachidonic acid to eicosapentaenoic acid. Given the connection between cardiovascular disease, DNA methylation, and alterations in PUFA profiles, this clinical investigation showcased potential cardiovascular protection through consistent consumption of Aronia juice.

Disturbed glucose metabolism is another risk factor in the development of cardiovascular diseases. Some findings indicate that chokeberry may have a positive effect on blood sugar levels. Bräunlich et al. (2013) proposed that distinct phenolic components found in chokeberry have the potential to act as effective inhibitors of α-glucosidase, thereby lowering blood sugar levels and potentially preventing the onset of diabetes.

Indeed, clinical trials have evaluated the benefits of two main phenolic components of Aronia berries, namely chlorogenic acid and quercetin, for the purpose of averting and managing cardiovascular ailments. There are studies examining the impact of a natural supplement comprising luteolin and chlorogenic acid on cardio-metabolic risk factors in individuals diagnosed with metabolic syndrome, as well as clinical trials investigating the impact of chlorogenic acids on the human vascular system. These studies aim to shed light on the potential cardioprotective effects of these compounds.

Clinical studies demonstrate that the active constituents with possible impacts to reduce the risk of cardiovascular disease are the potent phenolic compounds found in Aronia fruits, known for their strong antioxidant activity. Both chlorogenic acid and quercetin, among these phenolic compounds, could be considered as promising lead compounds for the development of novel substances for the management and prevention of cardiovascular disorders (Ren et al., 2022).

Anti-inflammatory effects

The Aronia berries is effective in preventing the development of chronic diseases because of its ability to reduce inflammation. Ohgami et al. (2005) demonstrated the anti-inflammatory effects of extract from *Aronia melanocarpa* on uveitis (It is the inflammation of a part or all of the uvea layer in the eye. It is an inflammatory disease.), an endotoxin-induced inflammatory disease, in rats. In another study, the ingestion of 100% cold-pressed fruit juice and oven-dried black chokeberry powder among individuals with slightly elevated blood pressure did not lead to significant alterations in the majority of inflammatory markers, but it was reported to decrease IL-10 (Interleukin 10 is classified as an anti-inflammatory cytokine and is alternatively referred to as a human cytokine synthesis inhibitory factor. It negatively regulates the immune response to microbe-derived antigens) and TNFa (or Necrosis Factor alpha is a cellular signaling protein implicated in systemic inflammation, and it's among the cytokines contributing to the acute phase reaction.) levels (Loo et al., 2016). Sikora et al. (2014a, 2014b) examined the impact of extract from black chokeberry on individuals diagnosed with metabolic syndrome and reported a slight increase in CRP (C-Reactive Protein is a blood examination that gauges inflammation within the body, irrespective of whether one is in a fasting or non-fasting state. It indicates the presence and degree of inflammation.) levels, which, however, did not decrease significantly following a period of two months consuming black chokeberry. Cyclooxygenases and inducible nitric oxide synthase are pivotal enzymes with proinflammatory roles, accountable for generating lipid mediators and nitric oxide, respectively, which are associated with the progression of many inflammatory diseases (Li et al., 2017). Jang et al. (2020) demonstrated that the Aronia bioactive fraction inhibits the production of COX-2 and iNOS in airway epithelial cells and reduces the secretion of reactive oxygen species, inducing cell cycle arrest and providing clear evidence for its anti-inflammatory activity.

Antidiabetic effects

Aronia fruits exhibit potential antidiabetic activity due to their ability to combat oxidative stress triggered by hyperglycemia (Banjari et al., 2017). Research has indicated that black chokeberry can positively impact β cells by shielding them from the detrimental consequences of oxidative stress (Sidor and Gramza-Michałowska, 2019). According to Rugină et al. (2015), the anthocyanin component of black chokeberry curtailed the harmful impact of glucose on pancreatic β cells (TC-3) in mice, leading to an enhancement in β cell viability. The extract from black chokeberry resulted in a noteworthy decrease in the concentration of reactive oxygen species in H_2O_2-exposed β cells. In a diabetic animal model studied by Mu et al. (2020), male Wistar rats (approximately 200 g) were given Aronia fruit ethanol extract (100 mg/kg) for eight weeks, resulting in significant reductions in blood glucose and serum insulin levels, insulin resistance degrees, and improved glucose tolerance level and hepatic glycogen.

Phenolic compounds derived from natural sources play a role in regulating carbohydrate and lipid metabolism, as well as blood sugar levels. They also mitigate insulin resistance, oxidative stress, and inflammation. Consequently, they have garnered widespread attention for their potential in managing and preventing diabetes (Dragan et al., 2015; Chen et al., 2021). For instance, ellagic acid derived from Aronia berries has been found to reduce hepatic oxidative stress and insulin resistance in a type 2 diabetic animal model. When ellagic acid (50 mg/kg) was administered daily to 11-month-old female Goto-Kakizaki rats for 28 days, blood sugar and insulin resistance were significantly reduced (Park et al., 2013). This points to the compound's antidiabetic effect for the treatment of hepatic complications in type 2 diabetes (Polce et al., 2018).

Monosaccharides like glucose and fructose are taken up by the small intestine, whereas disaccharides and polysaccharides are converted into monosaccharides within the intestine through enzymatic processes involving α-glucosidase and pancreatic α-amylase. Inhibition of α-glucosidase leads to reduced carbohydrate breakdown, altering the digestive process to occur in the latter portion of the small intestine, consequently decreasing the absorption of glucose into the bloodstream. This approach is regarded as a promising tactic to decrease levels of glucose in the blood and potentially alleviate complications associated with diabetes (Zhang et al., 2021). The chemical constituents found in the leaves of black chokeberry exhibit strong antioxidant characteristics and are capable of inhibiting the activities of α-amylase and α-glucosidase. This suggests significant potential for their use in potential treatments for both Alzheimer's disease (AD) and type 2 diabetes. (Zdunić et al., 2020). Research indicates that the consumption of chokeberry juice can lead to a decrease in glucose levels following an oral glucose tolerance test. Furthermore, it can notably diminish the activities of dipeptidyl peptidase IV, α-glucosidase, and angiotensin-converting enzyme in a manner that correlates with the dosage administered (Kumar et al., 2011). In a separate investigation, 35 individuals diagnosed with type 2 diabetes integrated phenol-rich Aronia juice (150 mL thrice daily, 50 mL per intake) into their conventional diabetes treatment. The patients displayed enhanced health conditions, suggesting that Aronia juice holds potential as a promising approach for diabetes mellitus prevention and management (Milutinović et al., 2019).

Support can be provided for treating diabetes or preventing metabolic syndrome by agents that aid in the absorption of carbohydrates and fats in the digestive system. It has been found that black chokeberry polyphenols also inhibit lipase activity, such as glucosidase (Sidor et al., 2019). Studies conducted on rats fed a high-fructose diet and treated with black chokeberry extract have shown that it lowered their blood glucose levels and improved lipid profiles (Qin and Anderson, 2012). Other research has demonstrated that black chokeberry extract lowers glucose levels in rats induced with hyperglycemia, obesity, and high-fat diets (Takahashi et al., 2015), as well as insulin-resistant mice treated with black chokeberry extract administered at levels of 100 and 200 µg/kg over a span of eight weeks (Park and Park, 2011). Yamane et al. (2017) noted that consuming chokeberry juice before meals reduced postprandial blood sugar levels. However, some other studies on black chokeberry products have shown no significant change in glucose levels in obese, hypertensive, or healthy individuals (Kardum et al., 2014a; Kardum et al., 2014b; Kardum et al., 2014c; Kardum et al., 2015; Loo et al., 2016).

Lipińska and Jóźwik (2018) demonstrated the ability of black chokeberry pomace to induce hypoglycemic effects in Merino lambs. In the control group, the glucose level measured 3.38 mmol/L, whereas the experimental groups that received 150 and 300 g of black chokeberry per kilogram of feed exhibited glucose levels of 2.42 and 1.55 mmol/L, respectively. Previous studies have indicated that the ample presence of niacin and anthocyanins in chokeberries contributes to their beneficial effects. Patients with hypercholesterolemia treated with daily chokeberry juice for 6 weeks showed a decrease in low-density lipoprotein cholesterol, triglyceride levels, and total cholesterol, as well as an increase in high-density lipoprotein cholesterol levels. Chokeberry juice assisted in their improvements without any pharmacological treatment (Valcheva-Kuzmanova et al., 2007).

High-fat diet-induced liver damage is closely associated with inflammation. Cyanidin-3-O-galactoside from black chokeberry has been shown to alleviate liver damage and inhibit the secretion of pro-inflammatory factors caused by a high-fat diet (Jiao et al., 2021). Individuals with diabetes who consumed 200 mL of black chokeberry juice on a daily basis for a period of three months observed a notable decrease in fasting blood glucose levels (Pinent et al., 2004); beneficial effects of black chokeberry juice on cholesterol and HbA1c-glycosylated hemoglobin lipid levels have been observed (Bell et al., 2006).

As summarized above, *Aronia* fruits have the potential to exhibit anti-type 1 diabetes and anti-type 2 diabetes activities, primarily due to the contribution of their existing phenolic compounds. These substances exert their antidiabetic effects by alleviating the oxidative stress induced by elevated blood sugar levels (Ren et al., 2022).

Antimicrobial effects

Much like their antioxidative properties, the antibacterial efficacy of plant extracts originates from the existence of phenolic compounds (Staszowska-Karkut and Materska, 2020). In fruit crops, polyphenols serve as remarkably efficient antimicrobial agents. The synthesis of flavonoids in plants is recognized as a defensive reaction to microbial infections; therefore, their *in vitro* effectiveness against a wide range of microorganisms is not surprising (Jurikova et al., 2017). Kim et al. (2020) reported that Chokeberry extracts showed *in vitro* bacteriostatic activity against *Escherichia coli* and *Staphylococcus aureus,* while leaf extracts exhibited inhibitory effects on the growth of Bacillus cereus. An examination of microbial activity against ten distinct pathogens demonstrated that proanthocyanidins exhibited the highest efficacy as antimicrobial agents (Pavlovic et al., 2015). Tian et al. (2018) indicated a direct connection between the overall phenolic content and the antibacterial effects against *Staphylococcus aureus* and *Bacillus cereus.* They emphasized that ellagitannins and isorhamnetin di- and tri-glycosides are the primary inhibitors, while the composition profiles significantly influence the antibacterial potential of plant extracts. According to Alves et al. (2013), the effectiveness of phenolic acids as antibacterial agents primarily hinges on the existence of carboxyl groups and the arrangement of substitutions on the benzene ring. Certain researchers have demonstrated that the quantity of hydroxyl groups within molecules can impact the antimicrobial potential of phenolic compounds, and the addition of sugar molecules to flavonols can diminish their efficacy in inhibiting growth (Puupponen-Pimiä et al., 2001; Rauha et al., 2000).

In a study conducted by Cvetanović et al. (2018), the antimicrobial effects of extracts derived from Aronia leaves were examined against two types of gram-positive and four types of gram-negative bacterial strains, and the extract's ability to combat fungal activity against two fungal species was also evaluated. The researchers conducted a comparison between the antimicrobial efficacy of Aronia extracts and amracin (a tetracycline antibiotic). They observed that the leaf extracts demonstrated antibacterial effectiveness that was fourfold greater against P. vulgaris and fifteenfold stronger against Proteus mirabilis in comparison to amracin. In another study, Chojnacka et al. (2020) demonstrated that *Aronia melanocarpa* fruit juice inhibited the replication of influenza viruses in their early stages and exhibited *in vitro* and *in vivo* effectiveness against various subtypes of influenza viruses. The ability to combat influenza was attributed to two polyphenolic compounds, namely myricetin and ellagic acid. Lately, there has been an observation that diverse plant species harbor biologically active substances, notably polyphenols. These compounds exhibit efficacy in addressing a range of illnesses, especially when combined synergistically, and function as natural inhibitors of viral enzymes. Besides other phytochemicals, ellagic acid and quercetin have shown potential antiviral activity against SARS-CoV-2 when interacting with viral proteins (Zhang et al., 2020).

Anticancer effects

Chokeberry, like other fruits, is an excellent reservoir of polyphenolic compounds with anti-tumor potential in both animals and humans. The antitumor activity is primarily associated with chlorogenic acids, certain cyanidin glycosides, and quercetin derivatives (Jurendić and Ščetar, 2021). In one study, the antioxidative capacity of Aronia berries was found to be associated with their anthocyanin content and total proanthocyanidin, and the present cyanidin glycosides were shown to inhibit cancer cell proliferation (Rugină et al., 2012). Commercial extracts of red, purple, and black chokeberries underwent analysis for their overall phenolic content and antioxidants, and only the black chokeberry extract was found to be active against HT-29 cells; this activity was shown to be related to the overall phenolic composition, antioxidative potential, and quantities of caffeic and chlorogenic acids (Gill et al., 2021).

In recent times, research has been undertaken to explore chokeberry's defensive mechanisms against cancer and its anti-cancer activity on tumor cell lines (Zhao et al., 2004; Bermúdez-Soto et al., 2007). Black chokeberry has been reported to have the potential to prevent the development of colon cancer, leukemia, and breast cancer, and there are also documented accounts of its preferential influence on cancer stem cells (Sidor et al., 2019). A recent examination explored the impact of black chokeberry fruit juice on mouse embryonic cancer stem cells (P19) and revealed its ability to impede the process of carcinogenesis (Sharif et al., 2013). Chokeberry juice can serve as a raw material for the production of various polyphenolic compounds, including those with antitumor activity (Sidor et al., 2019). Moreover, there are reports suggesting that Aronia leaf extract demonstrates anti-cancer effects by restraining the growth of SK-Hep1 human hepatoma cells and preventing the metastasis of cancer cells (Hwang et al., 2018).

Oxidative stress is among the indications of cancer. It has the potential to negatively impact the progression of the illness and contribute to the emergence of additional health disorders. Anticancer medications elevate oxidative stress within platelets and interfere with their physiological functions. Studies have shown that black chokeberry extract exhibits radical-scavenging inhibitor effects on platelets obtained from individuals diagnosed with breast cancer (Sidor et al., 2019). In the studies conducted by Kędzierska et al. (2013a, 2013b), *in vitro* experiments involving black chokeberry extract revealed a reduction in the levels of superoxide anion radicals in platelets obtained from all female groups that were tested. The extract was able to cleanse the radicals in platelets of diseased women by 8.7% to 35.0% and in platelets of healthy women by up to 60.7%.

It is believed that the effect of Aronia extract on platelets is due to its antioxidant activity, which is mediated through the scavenging of free radicals by polyphenols. Furthermore, it has been suggested that polyphenols increase the activity of superoxide dismutase, an important enzyme in regulating platelet function, thereby enhancing the endogenous antioxidant capacity (Sidor et al., 2019). In a study by Gao et al., (2018), it was shown that phenolic compounds found in Aronia fruits robust antioxidant potential and cytotoxic effects against HepG2 human liver cancer cells, indicating the potential of chokeberry in preventing the progression of liver tumors.

Cvetanović et al. (2018) discovered that black chokeberry extracts exhibited pronounced sensitivity towards human colorectal adenocarcinoma LS-174T cells, with IC50 values of 5.44 μg/ml for fruit extract and 1.38 μg/ml for leaf extract, compared to 7.46 μg/ml for the anticancer drug cisplatin. Additionally, the fruit extract showed cytotoxicity against HeLa cervical cancer cells, and this effect was even higher than its effect on human colorectal adenocarcinoma LS-174T cells and human A-549 lung cancer cell lines. In their study, Cvetanović et al. (2018) found that the leaf extract more strongly restrained the growth of cancer cells compared to cisplatin and fruit extract.

It is recognized that cigarette smoke harbors elevated concentrations of cancer-causing compounds. Studies have demonstrated that short-term exposure of mice to cigarette smoke resulted in a range of unfavorable alterations, including weight loss, micronucleated erythrocytes, and histopathological changes in the lungs, liver, and bladder (Sidor et al., 2019). Balansky et al. (2012) documented that water-based solutions of black chokeberry and strawberry extracts restricted the development of pulmonary emphysema, lung adenomas, and liver degeneration induced by cigarette smoke. As discussed above, Aronia fruits and their components, especially the main phenolic compounds found in the findings from clinical trials, suggest that Aronia fruits hold promising potential for the creation of novel anticancer agents.

Conclusions and Suggestions

Aronia (*A. melanocarpa*) possesses numerous positive pharmacological activities that could exert beneficial impacts on human well-being. Chokeberry fruit and its products serve as a source of various compounds that promote health and offer beneficial effects (Zhang et al., 2021). The main components of *A. melanocarpa* related to nutrition and health include polyphenols, sugars, minerals, and vitamins. Multiple *in vitro* and *in vivo* research have affirmed that these compounds showcase a diverse array of advantageous and physiological effects, including antioxidant, antidiabetic, anti-inflammatory, blood pressure-lowering, antiviral, anticancer, antiplatelet, and antiatherosclerotic activities (Jurendić and Ščetar, 2021).

As previously discussed and highlighted in this review, *Aronia* fruits demonstrate potent antioxidant activity and possess the capacity to hinder the activity of various radical species through distinct mechanisms. Therefore, these compounds hold promise in terms of preventing and potentially managing conditions such as cancer, cardiovascular diseases, diabetes, obesity, and neurological disorders (Sidor et al., 2019; Yang et al., 2021; Jurendić and Ščetar, 2021; Kokotkiewicz et al., 2010; Sun et al., 2017). *Aronia* has also found applications in addressing different types of cancers, including breast cancer, intestinal cancer, and leukemia. The therapeutic impacts of chokeberry hold significance in managing various human ailments, encompassing conditions such as hyperlipidemia, hypertension, hypercholesterolemia, diabetes, and cardiovascular diseases. Aronia berries can provide an essential strategy for enhancing human health. Chokeberry stands out as one of the most abundant sources of consumable polyphenols (Zhang et al., 2021).

Polyphenols have been documented to have beneficial health effects, particularly in terms of antioxidant potential. Besides polyphenols, the biological effects are closely linked to other prominent constituents present in chokeberries, like anthocyanins, proanthocyanidins, flavan-3-ols, and flavonol glycosides, which play a pivotal role in conferring antioxidant capabilities (Ćujić et al., 2018). Numerous literature reports on Aronia fruits have highlighted that their biological characteristics stem from the combined action of all phenolic compounds rather than isolated individual components. This presents novel avenues for research in this domain due to the diverse array of phenolic compounds present in the fruits (Negreanu-Pirjol et al., 2023).

Currently, chokeberry products available in the market mainly include fresh and dried fruits, fruit juices, jams, and jellies (Ćujić et al., 2018). Studies indicate that chokeberry possesses considerable nutritional value, and its derivatives hold substantial prospects for development (Zhang et al., 2021). However, a problem related to chokeberry polyphenols is their low stability, as none of the mentioned products provide resistance against long-term stability, oxygen, light, and moisture. Promisingly, new microencapsulation techniques may offer a solution to overcome the issues of polyphenol instability, low bioavailability, and deterioration (Ćujić et al., 2018).

However, current research tends to focus in the context of preventing and managing human illnesses, overlooking the investigation of biological toxicity, optimal consumption of polyphenols, and potential adverse effects of excessive intake such as tannins present in chokeberry. Therefore, in the future, there is a need to explore the effects and safety mechanisms of chokeberry on humans. It is anticipated that the future will witness a rise in the widespread acceptance of chokeberry-based food products, leading to an expanded consumer inclination towards functional foods (Zhang et al., 2021).

Recognizing the significance of *Aronia melanocarpa* items and residuals in human dietary intake, along with their contributions to human health, holds substantial significance. Existing literature provides data indicating the potential of *Aronia melanocarpa* as a nutrient-rich and healthy dietary food with numerous functions and benefits (Jurendić and Ščetar, 2021). The polyphenols found in Aronia are recognized as paramount dietary antioxidants, manifesting robust safeguards against cellular oxidative harm and counteracting oxidative stress both directly and indirectly (Ćujić et al., 2018).

Comprehensive research involving human studies is needed to understand the effectiveness, safety, mechanisms of action, activity, and interactions of chokeberry with other compounds, as well as to determine the recommended intake.

Competing Interests

The author declare that have no competing interests.

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