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# Active ingredients of blueberry pomace: A comprehensive review of isolation, identification, health benefits and food applications

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ABSTRACT

Blueberry pomace is a valuable source of a wide range of active compounds and nutrients and is receiving increasing research attention. However, limited attention has been paid in the literature to the nutritional properties and practical applications of blueberry pomace. In this paper, we review the methods used to extract bioactive compounds from blueberry pomace, study their health effects and explore the prospects for their application in the food industry, such as fermented beverages, nutritional supplements or natural colors. In addition, recent studies have examined the content of various active ingredients such as flavonoids, vitamins, and dietary fiber and suggested the validity of the corresponding extraction methods. In addition, these compounds have great potential in human health, such as antioxidant, hypoglycemic, improvement of cognitive impairment and gut health. This analysis also highlights the bioavailability of the active ingredients in blueberry pomace. Thus, blueberry pomace offers a wide field of scientific and technological exploration, but significant challenges must be faced in order to optimize its utilization and promote further research on extraction, applications, and innovative methods.

## 1. Introduction

Blueberries (*Vaccinium spp.*), originating from North America, are extensively cultivated in cool, sunny climates and have gained widespread popularity worldwide for their unique blend of sweet and tart flavors, as well as their exceptional nutritional value (Zhang et al., 2022). As shown in Fig. 1, blueberries are categorized into four species based on morphology: rabbit-eye blueberry (*V. virgatum*), northern high shrub (*V. corymbosum*), southern high shrub (*V. formosum*), and low shrub (*V. angustifolium*) (Bai et al., 2023). However, the substance content varies among blueberry species, and according to Li et al. (2024), who compared highbush (HB) and rabbiteye (RB) blueberries, it is clear to us that the total phenol content of RB's pericarp (55.39 mg GAE/g DW) and pulp (8.59 mg GAE/g DW) was higher than that of HB's pericarp (51.69 mg GAE/g DW) and pulp (7.26 mg GAE/g DW), while total phenols were not detected on seeds of HB and RB. Blueberries are classified as "super fruits" due to their remarkable anthocyanin content, which is comparable to that found in purple sweet potatoes, contributing significantly to their high nutritional value among various fruits (Pérez et al., 2022). The International Food and Agriculture Organization (IFAO) lists blueberries as one of the "top five health foods for humans" (Liu, Qiu, et al., 2021). Blueberries have been used in recipes around the world for centuries, and their by-products have recently been utilized as nutraceuticals and health-promoting ingredients that are receiving increased public attention. Blueberry pomace, as a major by-product of blueberry processing, retains many of the active ingredients in blueberries, especially proteins, anthocyanins, polysaccharides, acidic components, and astragalus. Although the active ingredients of blueberries have been detailed in the scientific literature, blueberry pomace has been poorly understood, so further analysis of the health benefits of the active components contained in blueberry pomace is urgently needed (Shan et al., 2023).

In recent years, with the increasing number of people suffering from multiple non-communicable diseases (NCDs) such as cardiovascular disease (CVD), diabetes, hypertension, metabolic syndrome (MetS), cognitive functioning and cancer, people are slowly starting to move

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towards a healthier lifestyle (Chang et al., 2019). In addition, the extensive research and promotion, around the world, of the Mediterranean diet pattern with berries (especially blueberries), seafood, nuts, whole grains, vegetables, and moderate intake of red wine as key elements, has led to a growing interest in healthy food choices among consumers (Tucker, 2017). Contemporary consumers seek functional foods, particularly nuts, fruits, vegetables, and high value-added by-products, as integral components of a healthful lifestyle aimed at maintaining optimal fitness and wellness. Nowadays, healthy snacks obtained by derivation of blueberry pomace active ingredients or as fermented beverages (Trajkovska et al., 2024), bakery products (Šaric et al., 2018), functional food products (Tran & Tran, 2021), plant-based meat products (Ścibisz & Ziarno, 2023), snack foods (Nakov et al., 2020) and natural coloring raw materials (Wang et al., 2024) are used in several areas of food. This provides an opportunity to transform blueberry pomace into a renewable resource and play a role in the circular bioeconomy. The study of blueberries and their byproduct, blueberry pomace, is receiving increasing attention in the context of current dietary health trends. While there has been a significant amount of research focused on the nutritional value and health benefits of blueberries themselves, equal attention should be given to exploring the applications and benefits of their by-products. A comprehensive and organized review is needed to provide better information to those interested in this topic.

## 2. Active ingredients and their properties

Blueberries are consumed both as fresh fruit and, in significant proportions, undergo processing to yield juice and wine along with 20–30 % of the pomace being discarde (Cheng et al., 2020) (Fig. 2). The active components in blueberry pomace include flavonoids (flavonols, anthocyanins), phenolic acids, astragalus, lignans and organic acids in various forms and Fig. 1 demonstrates the chemical structure of the main phenolic substances in blueberry pomace. The polyphenol content of blueberry pomace (28 %–70 %) is comparable to grape pomace (70 %) (Bamba et al., 2018). Table 1 compares the composition and properties of various berries and their by-products (blackcurrant, grape, pomegranate, kiwi, passion fruit, papaya) with those of blueberries and blueberry pomace.

### 2.1. Flavonols

Flavonols are the major flavonoids in blueberries, which are synthesized by flavonoid 3′ hydroxylase (F3H) and flavonol synthase (FLS) (Li et al., 2023a). Previous studies have shown that the flavonoid content of blueberry pomace (11.3426 mg/100 g) was much higher than Blackcurrant pomace (13.8 mg/100 g) (Azman et al., 2022; Wang et al., 2018), as shown in Table 1. The high nutritional value of fresh blueberry fruits promotes increased utilization of blueberry residues. Researchers further radicalized used various methods to extract flavonoids from blueberry pomace. It was found that there were significant differences in the extraction rates among the different extraction methods, as well as among different parts of the blueberry. For instance, by employing ionic molecular weight, Mass Spectrometry n (MSn), and UV–visible spectroscopy to analyze the flavonoids in blueberry fruits, blueberry pomace, and blueberry leaves respectively, extraction rates of 11.555 g/100 g, 14.648 g/100 g, and 19.810 g/100 g were observed (Li et al., 2013). Lončarić et al. (2020) used high voltage discharge (HVED), pulsed electric field (PEF) and ultrasound-assisted extraction (UAE) of flavonoids obtained from blueberry pomace at contents ranging from 4.453 to 15.754 mg/100 g. While most of the current research focuses on extracting flavonoids from fresh blueberry fruit rather than from blueberry pomace, these infrequently reported studies suggest that blueberry pomace may serve as a potential source of flavonoids. However, the current research on methods to extract flavonoids from is limited, and further exploration of efficient extraction techniques will facilitate its application.

### 2.2. Anthocyanins

Anthocyanins are the main active constituents in blueberries, with levels as high as 558–815 mg/100 g, which are much higher than those of raspberries (365 mg/100 g), black-fruited chokecherry (190–270 mg/100 g), Marion raspberries (317 mg/100 g), and other edible plants, including black beans and black rice, and is predominantly enriched in blueberry pericarp (James et al., 2022). Studies have shown that the anthocyanin content of blueberry pomace can be 20–30 % of the dry weight, a percentage even higher than that of fresh blueberries. There are several methods for extracting blueberry anthocyanins, of which the extraction of anthocyanins from blueberry pomace with acidic water (1 % citric acid) minimizes extraction time and does not require advanced equipment to increase yields (Ferreira et al., 2020). In addition, ultrasound-assisted extraction, a new green extraction method based on the polarity and solubility of anthocyanins, significantly increased the yield of anthocyanins from blueberry pomace with an optimal yield of 108.23 mg/100 g DW (Zhang et al., 2022). Multi-frequency ultrasonic extraction was also found to increase the yield of anthocyanins by 15.26 % and 5.45 % for triple-frequency (25 + 40 + 80 kHz) and dual-frequency ultrasonic extractions, respectively, as compared to single-frequency (25 kHz) and the antioxidant activities (DPPH, hydroxyl radical scavenging and reducing capacities) of the anthocyanins were higher than those of anthocyanins extracted without ultrasonic extraction (Hu et al., 2021). At present, the enzymatic extraction of anthocyanins from blueberries and blueberry pomace is less applied, but has a broad development potential. Considering various factors that affect the stability and yield of anthocyanins, such as raw material properties, varieties, different application scenarios, and extraction conditions, future research can employ combined extraction methods to optimize technical parameters. Additionally, new strategies for more efficient and environmentally friendly blueberry pomace anthocyanin production can be developed, including ultrasonic-assisted solvent extraction, enzyme-assisted extraction combined with physical methods, supercritical fluid

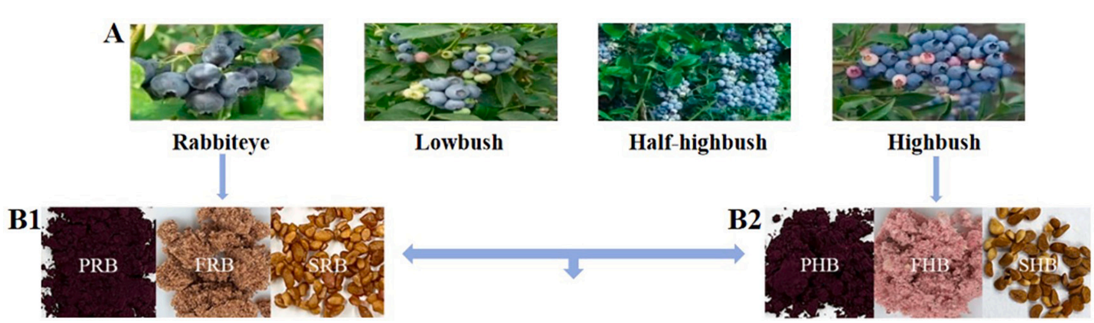


**Fig. 1.** (A) Plant and fruit morphology of different blueberry varieties (Bai et al., 2023). (B1) Visual appearance of peels (PRB), flesh(FRB) and seeds (SRB) of rabbiteye blueberry (Li et al., 2024). (B2) Visual appearance of peels(PHB), flesh(FHB) and seeds (SHB) of highbush blueberry (Li et al., 2024).

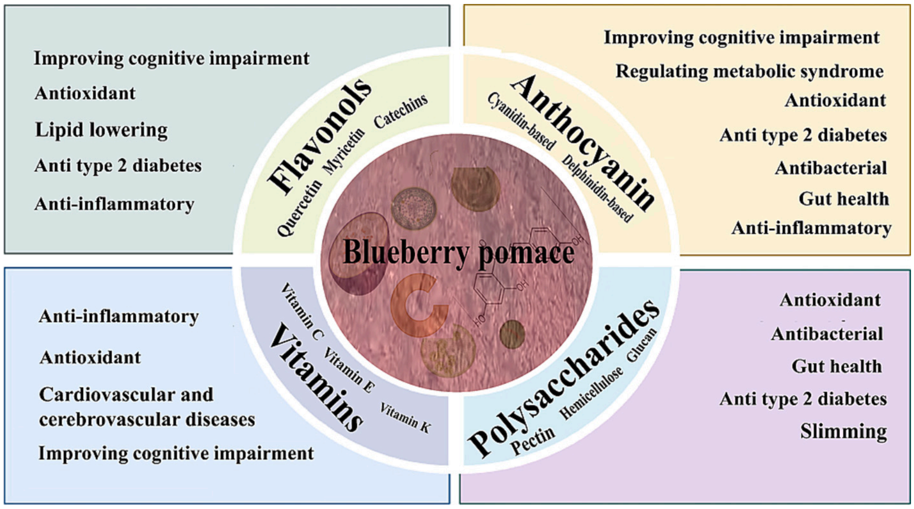


**Fig. 2.** Active ingredient produced by blueberry pomace.

**Table 1**
Comparison of nutritional components between berries/berry by-products and blueberries/blueberry pomace.

| Berries/ By-products compound | Blueberries/ Blueberry pomace | Blackcurrant/ Blackcurrant pomace | Grape/Grape pomace | Pomegranate/ Pomegranate pomace | Kiwifruit/ Kiwifruit pomace | Passionflower/ Passionflower pomace | Papaya/ Papaya pomace |
|---|---|---|---|---|---|---|---|
| Flavonoids | – | 5.25 mg /g (Paunović et al., 2019) | – | 150 mg/100 g (Sahu et al., 2020) | 6.45 mg/g (Zhao et al., 2021) | 0.60 mg/g (Sun et al., 2023) | 21.93 μg/mg (Jadaun et al., 2023) |
| | 11.3426 g/100 g (Wang et al., 2018) | 13.8 mg /100 g (Azman et al., 2022) | 254.1–479.7 μg/g (Vasyliev et al., 2020) | – | 1.97 mg/g (Ilie et al., 2022) | 0.0047 g/kg (Silva et al., 2017) | 39.41 μg/mg (Jadaun et al., 2023) |
| Phenolic acids | 690 mg/100 g (Hellström et al., 2024) | 815 mg/100 g (Ejaz et al., 2022) | – | 1849–2991 mg / L (Topalović et al., 2020) | – | – | 0.46 % (Jadaun et al., 2023) |
| | 62.547 mg/100 g (Lončarić et al., 2020) | 69.3 mg/k g (Michalska et al., 2017) | 479.7 μg/g-604.51 μg/g (Vasyliev et al., 2020) | 3115 μg/g (Yenil et al., 2022) | – | – | 0.27 % (Jadaun et al., 2023) |
| Stilbenes | – | – | 896.25 μg/kg (Nishiyama et al., 2023) | – | – | 3.18 μg/g (Krambeck et al., 2020) | – |
| | – | – | 1.061 mg 100/g (Rätsep et al., 2020) | – | – | – | – |
| Anthocyanins | 1380 mg/100 g (Hellström et al., 2024) | 160–411 mg/100 g (Ejaz et al., 2022) | - - | 25 mg/100 g (Ghasemi-Soloklui et al., 2023) | 176.53 mg/kg (Ye et al., 2023) | – | 1776.69 mg /100 g (Lv et al., 2024) |
| | 44.2 g/100 g (Zhang et al., 2017) | 215 mg/100 g (Ejaz et al., 2022) | 453.57 mg/kg (Nishiyama-Hortense et al., 2023) | 1840.5 μg/g (Díaz-Mula et al., 2019) | 694.76 mg/kg (Ye et al., 2023) | 2.58 mg/g (Ghada et al., 2020) | – |
| Lignans | – | – | – | – | – | – | – |
| | – | – | – | – | – | – | – |

combined with ultrasonic extraction, microwave-assisted extraction combined with natural deep eutectic solvent extraction. Although anthocyanin extraction from blueberries and blueberry pomace has made some progress, it still faces challenges such as stability, extraction efficiency and environmental impact. Future research needs to focus on developing fast, efficient and environmentally friendly extraction methods, while ensuring the bioactivity, bioavailability and yield of anthocyanins. In addition, exploring new application areas and improving market acceptance are also key to promoting the high-value utilization of blueberry pomace.

### *2.3. Phenolic acids*

Phenolic acids are a subclass of polyphenols and consist of two types, namely hydroxybenzoic acid and hydroxycinnamic acid (Van et al., 2017). Blueberries contain 87.56 times more phenolic acids than passion fruit (Hellström et al., 2024). In addition to this, the phenolic acid content of blueberry pomace was also high relative to grape waste (Table 1). Namely, Lončarić et al. (2020) obtained 62.547 mg/100 g phenolic acid from blueberry pomace treated with ethanol-based solvent and pulsed electric field with energy input of 41.03 kJ/kg. In contrast, 47.97 mg/100 g of phenolic acid was extracted from treated grape pomace (Vasyliev et al., 2020). The bound phenolic acids found in blueberry pomace were mainly quercetin, kaempferol and their rutin conjugates, which could be extracted by microbiological (*Lactobacillus plantarum* J26) methods at a rate of up to 176.11 ± 1.58–4269.21 ± 103.30 μg GAE/mL) (Zhang et al., 2021). In addition, the free phenolic acid content of blueberry pomace was dominated by protocatechuic acid (0.56–1.91 mg/100 g FW), vanillic acid (0.55–2.68 mg/100 g FW) and chlorogenic acid (6.81–9.54 mg/100 g FW) (Shi et al., 2020). Gallic acid (0.14–0.35 mg/100 g FW), ellagic acid (0.17–0.72 mg/100 g FW), caffeic acid (0.62–2.45 mg/100 g FW), ferulic acid (0.02–0.76 mg/100 g FW) were also present in small amounts in blueberry pomace (Cheng et al., 2020). Overall, the phenolic acids in blueberry pomace are dominated by free forms of chlorogenic and vanillic acids. The bound forms of phenolic acids are hydroxycinnamic acid structures such as quercetin and kaempferol, and these bound phenolic acids are not directly absorbed by the small intestine, but can enter the colon intact and subsequently be released through fermentation by gut bacteria, which may play a key role in intestinal health (Guo et al., 2020). The means of extracting phenolic acids and studies on other highly nutritious fruit wastes investigated are found to be lacking and still need to be further explored.

### 2.4. Stilbenes

Stilbenes are a naturally occurring dimethyl ether analog of polyphenols and resveratrol that provide critical antipathogenic defense for

**Table 2**
Extraction method and yield of active ingredients of blueberry pomace.

| Active ingredient (s) | Extraction methods | Extraction condition | Yield | References |
|---|---|---|---|---|
| Flavonoids | High-voltage Discharge | Ethanol concentration (*v/v*) 50 % + hydrochloric acid concentration (*v/v*) 1 %, pulse 100, electric field 20 kV/cm | 15.754 mg/100 g | Lončarić et al. (2020) |
| | Ultrasonic-negative pressure cavitation extraction | Ethanol concentration (v/v) 68.61 %, ultrasonic power 0.36 W/cm$^2$, negative pressure − 0.07 Pa, extraction time 15 min, solid-liquid ratio 1:30 g/mL, extraction temperature 50 °C | 11.3426 g/100 g | Wang et al. (2018) |
| | Ultrasound-assisted extraction | Ethanol concentration/water (v/v) 50 %, sonication time 90 min, extraction temperature 60 °C; waste mass *vs.* ethanol volume 1:17.36, processing time 1000 s | 1.941 g/100 g; 1.410 g/100 g | Bamba et al. (2018); Piechowiak et al. (2021) |
| Phenolic acids | Pulsed electric field | Ethanol concentration (v/v) 50 % + hydrochloric acid concentration (v/v) 1 %, pulse 100, electric field 20 kV/cm | 62.547 mg/100 g | Lončarić et al. (2020) |
| | Microbiological method | Folinjolol reagent (0.1 mL) and 7.5 % sodium carbonate solution (0.2 mL) were added to the blueberry pomace at an extraction temperature of 25 °C and an extraction time of 40 min | 176.11 ± 1.58 μg /mL | Zhang et al. (2021) |
| Stilbenes | – | – | – | – |
| Anthocyanins | High-voltage Discharge | Methanol concentration (v/v) 50 % + hydrochloric acid concentration (v/v) 1 %, frequency 50 Hz | 175.732 mg/100 g | Lončarić et al. (2020) |
| | Ultrasonic-negative pressure cavitation extraction | Ethanol concentration (v/v) 68.61 %, ultrasonic power 0.36 W/cm$^2$, negative pressure − 0.07 Pa, extraction time 15 min, solid-liquid ratio 1:30 g/mL, extraction temperature 50 °C | 21.2722 g/100 g | Wang et al. (2018) |
| | Deep eutectic solvents combined with ultrasonic technology | Choline chloride: 1,4-butanediol (1:3 M ratio), 29 % water, extraction temperature 63 °C; liquid-solid ratio 36:1 (*v/w*) | 1.140 g/100 g | Zhang et al. (2023) |
| | Ultra High Pressure Extraction | Ethanol concentration (v/v) 60 % + 12 M hydrochloric acid extraction solvent (v/v = 99:1), pressure 500 MPa, extraction time 3 min | 44.2 g/100 g | Zhang et al. (2017) |
| | Ultrasound-assisted extraction | The relationship between waste mass and ethanol volume was 1:17.36, and the extraction time was 1000 s; The waste-to-liquid ratio (1:20, *w*/w), the extraction temperature was 40 °C, the ultrasonic power was 400 W, and the extraction time was 40 min | 1.35–38.44 g/100 g; 108.23 mg/100 g | Piechowiak et al. (2021); Zhang et al. (2022) |
| | Microwave-assisted extraction | Ethanol concentration (v/v) 60 % + 12 M hydrochloric acid as extraction solvent (v/v = 99:1), microwave power 360 W, extraction time 150 s | 36.76 g/100 g | Zhang et al. (2017) |
| | Heated extraction | Ethanol concentration (v/v) 60 % + 12 M hydrochloric acid extraction solvent (v/v = 99:1), extraction temperature 60 °C, extraction time 1 h | 32.43 g/100 g | Zhang et al. (2017) |
| | Homogenisation - ultrasonic assisted extraction | Ethanol concentration (v/v) 70 % + 0.02 % of the antioxidant component rhamnosus acid, liquid-solid ratio 16 mL/ g, extraction temperature 55 °C, frequency 80 kHz, power 200 W, extraction time 40 min | 13.95 ± 0.37 mg /g | Jin et al. (2019) |
| Lignans | Chromatography combined with 95 % ethanol-H2O extracts | Ethanol concentration (v/v) 95 % | – | Li et al. (2019) |
| Dietary fibers | Convection drying | Extraction temperature 45 °C, extraction time 20 h | 56.41 % | Šaric et al. (2018) |
| | Chemical extraction | – | 40.16 % | Davis et al. (2018) |
| | SGD method | Blueberry pomace was vortexed with 0.05 M phosphate buffer, α-amylase (20 FAU/g), and 50 mM calcium chloride solution.After a 37 °C water bath, deionized water was added along with 0.2 % pepsin solution and 50 mM calcium chloride solution. The pH of the mixture was adjusted to 3 with 1 M hydrochloric acid and water bath at 37 °C for 2 h. Finally, 0.05 M phosphate buffer and duodenal juice were added, and the pH of the sample mixture was adjusted to 7 with 0.1 M sodium hydroxide, and the sample was incubated at 37 °C for 2 h | 42.68 % | Davis et al. (2018) |
| | NMKL 129 | – | 14.6 % | Hotchkiss Jr. et al. (2021) |
| Antitrophic factor | – | – | – | – |
| Total sugar | AOAC method | Blueberries were suspended in water, 5 % phenol (*w/v*) was added and vortexed vigorously for 5 s. Finally, concentrated sulfuric acid was added and gently vortexed | 19.41 % | Hotchkiss Jr. et al. (2021) |
| Vitamins | UHPLCMS/MS method | Extraction buffer (100 mM ammonium acetate, 1 % ascorbic acid, 0.2 % 2-mercaptoethanol, pH = 7.89) boiled | 118 μg/100 g | Zou et al. (2018) |
| Minerals | Organic solvent extraction | Extracted at a substrate-to-solvent ratio of 1:5 (w/ v) with 80 % ethanol concentration (v/v) | 0.193 % | Ross et al. (2017) |

plants (Wang and Sang, 2018). The distribution of stilbenes in blueberries is not exclusively limited to the fruit, but studies on the extraction of stilbenes from blueberry pomace in recent years have not yet been reported. Fern compounds have also been shown to provide preventive and therapeutic benefits in terms of their effects on antioxidant damage and inflammation (Nagarajan et al., 2022). Meanwhile, in ligand binding assays, resveratrol has been shown to bind with greater affinity to estrogen receptors, resulting in intestinal (stomach, intestines, and colon) and hepatic metabolites playing an important role in mediating the physiological effects of these compounds with a greater safety profile. Due to the lack of research related to stilbenes from blueberries, more research is needed to explore the potential of its application. Overall, stilbenes are novel, effective and safe drug candidates for the treatment of various diseases and disorders, but their extraction related studies are yet to be explored by researchers (Nagarajan et al., 2022).

### 2.5. Dietary fibers

Dietary fiber is a key structural component of plant cell walls, consisting of pectin, hemicellulose, cellulose and lipids. It is known as the 'seventh group of nutrients', and has obvious preventive and therapeutic effects on the NCDs (Zhao et al., 2018). Blueberries and blueberry pomace are also rich in dietary fiber, and the extraction methods for the active ingredients of blueberry pomace are shown in Table 2. It was found that the extraction content and extraction rate of dietary fiber from blueberry pomace could be obtained using convective drying, chemical, simulated gastrointestinal digestion (SGD), and (ANKOM A2000 Dietary Fiber Analyzer) NMKL 129 treatments with approximately 56.41 %, 40.16 %, 42.68 %, and 14.6 %, respectively (Davis et al., 2018; Šaric et al., 2018). Additionally, the ability of pectin to improve rheological properties and gel properties of food matrices is related to its degree of esterification. Based on these factors, improving the extraction of dietary fiber and pectin from blueberry pomace has become an innovative quality objective for biotechnology strategies and applications aimed at controlling or increasing the potential dietary fiber and pectin content of blueberry pomace and providing strategies for the high-value utilization of blueberry pomace and healthy diets (Šaric et al., 2018).

### 2.6. Other components

Blueberry pomace is also a good source of sugar, various vitamins and minerals (Cu, Fe, Ca, K, Mg, Mn) (Ross et al., 2017). The total sugar extracted from blueberry pomace alone has been reported to be as high as 19.41 % (Hotchkiss Jr et al., 2021). On the other hand, blueberry pomace is a good source of several minerals. Calcium (1899.78 μg/100 g), iron (54.19 μg/100 g), potassium (3661.51 μg/100 g), magnesium (526.03 μg/100 g), sodium (261.23 μg/100 g), and zinc (1.98 μg/100 g) are the main minerals in blueberry pomace (Chen et al., 2016). Ross et al. (2017) found that organic blueberry pomace contained at least five times more Ca (∼0.25 %) than organic cranberry pomace, cranberry ethanol soluble extract, and blueberry ethanol soluble extract. The bioavailability of these minerals remains to be studied. However, the factors that influence the accumulation of these nutrients have not been studied. Furthermore, how food processing affects the bioactivity and bioavailability of these nutrients in pomace also requires further exploration.

**Table 3**
Health benefits of blueberry pomace.

| Health effect (s) | Useful substance | Type of study | Major results | References |
|---|---|---|---|---|
| Antioxidant | flavonoids | *in vitro* | • ↑DPPH·, ↑FRAP, ↑TEAC | James et al. (2022) |
| | Anthocyanins | *in vitro; in vitro;in vitro* | • ↑DPPH·, ↑OH·, ↑FRAP,↑SOD,↓MDA | Hu, Li, Piechowiak et al. (2021) |
| | Phenolic acids | *in vitro* | • ↑DPPH·, ↑ABTS | Qiao et al. (2024) |
| | Total phenol | *in vitro* | • ↑α-Amylase inhibitory activity | Tian et al. (2020) |
| | Vitamins | *in vivo* | • – | Popović et al. (2022) |
| | Quercetin | *in vivo* | • – | Zaborowski et al. (2024) |
| Anti-inflammatory | All phenolic extracts | *in vitro* | • ↓Pro-inflammatory cytokine expression and inhibition of COX-2 activity *in vitro* | Kunrade et al. (2020) |
| | | *in vitro* | • ↓Inflammatory markers (COX-2, IL-1β) | Hoskin et al. (2018) |
| | | *in vivo* | • ↑Rabbit synovial cell HIG-82 | South et al. (2019) |
| | | *in vitro* | • ↓Inflammatory bowel disease | Driscoll et al. (2020) |
| Anti-type 2 diabetes | All phenolic extracts | *in vitro* | • ↓α-Glucosidase | Gonçalves et al. (2023) |
| | Anthocyanins | *in vitro* | • ↑Glucose intake, ↓Oleic acid lipid accumulation | Zhu et al. (2023) |
| | | *in vivo* | • ↓α-Glucosidase | Dermengiu et al. (2022) |
| | Polysaccharide-polyphenol conjugates | *in vitro* | • ↓α-Glucosidase | Campos et al. (2021) |
| | | *in vitro* | • ↓Glucose uptake by CaCO-2 monolayers | Campos et al. (2021) |
| Anti-fat | Anthocyanins | *in vivo* | • ↑Induction of gut microbiota imbalance in obese mice | Cheng et al. (2024) |
| Improvement of cognitive impairment | Extracts | *in vivo* | • ↑Alzheimer's disease mitigation by antioxidant capacity | Li et al. (2023b) |
| | Anthocyanins | *in vitro* | • ↑Neuroinflammatory inhibition | Kalt et al. (2020) |
| | Organic acids, minerals | *in vivo* | • ↑Neuroinflammatory inhibition | Duan et al. (2022) |
| | Vitamins | *in vivo* | • ↑Neuroinflammatory inhibition | Popović et al. (2022) |
| Antimicrobial and Improved Gut Health | Pectin polysaccharide | *in vitro* | • – | Qiao et al. (2024) |
| | Blueberries or their by-products | *in vitro* | • ↓TBARS number of samples | Babaoğlu et al. (2022) |
| | | *in vitro* | • ↓*Vibrio parahaemolyticus* | Sun et al. (2020) |
| | Anthocyanins | *in vitro* | • ↓Urinary tract infection | Cerezo et al. (2020) |
| | | *in vitro* | • ↓Growth of *Listeria monocytogenes*, *Escherichia coli* | Liu et al. (2021) |
| | All phenolic extracts | *in vitro* | • ↓*Enterococcus faecalis* ATCC 29212, *Bacillus cereus* ATCC 11778, *Listeria monocytogenes* LMG 16779, *Staphylococcus aureus* ATCC 25923 | Gonçalves et al. (2023) |
| | | *in vitro* | • ↓*Staphylococcus aureus* | Salaheen et al. (2017) |

**Abbreviations:** DPPH, 2,2-Diphenyl-1-picrylhydrazyl; FRAP, Ferric Reducing Antioxidant Power; TEAC, Tetraethylammonium Chloride; SOD, Superoxide Dismutase; MDA, Malonydialdehyde; COX-2, Cyclooxygenase-2; IL-1β, Interleukin-1β; HIG-82, Human Iridoid Gland Carcinoma Cells; TBARS, Thiobarbituric Acid Reactive Substance.

## 3. Health benefits of blueberry pomace and its biological response

As with other bioactives from plants, the various health benefits of blueberry pomace have been demonstrated in different *in vitro* and *in vivo* studies. Table 3 lists the active ingredients extracted from blueberry pomace and their biological effects, but few studies have focused on terpenoids and proteins from blueberry pomace.

### *3.1. Antioxidant effect*

The antioxidant effects of blueberry pomace extracts and isolates have been studied mainly *in vitro*. Most of these *in vitro* approaches are based on *in vitro* cell models and chemical assays (*e.g.*, reducing capacity, metal chelating capacity and lipid oxidation assays) (Piechowiak et al., 2021). Blueberry pomace anthocyanins (Piechowiak et al., 2021), phenolic acids (Qiao et al., 2024), flavonoids, and vitamins (Popović et al., 2022) have antioxidant activity to varying degrees. Anthocyanins are considered as the main antioxidant active substances in blueberry pomace as *in vitro* antioxidant activity is positively correlated with anthocyanin content (Bamba et al., 2018). In addition to the previously mentioned components, phenolic acids and quercetin may also be responsible for the antioxidant effects of blueberry pomace, as they both contain hydroxyl groups, carbonyl functional groups, and aromatic rings with hydrogen-donating, resonance-stabilizing, metal-ion chelating, and electrophilic substitution-reacting capabilities (Zaborowski et al., 2024). While *in vitro* antioxidant tests provide valuable preliminary data, they may not fully reflect the actual biological function of blueberry pomace *in vivo*. Therefore, animal and human clinical studies are essential to confirm these antioxidant effects and evaluate the efficacy of blueberry pomace and its derivative raw products.

### *3.2. Anti-inflammatory effect*

Under physiological conditions, inflammation is a protective response of the innate immune system. It can be triggered by varying levels of endotoxins, reactive oxygen species, cytokines, growth factors, and carcinogens, and has been associated with a variety of diseases such as atherosclerosis, cardiovascular disease, cancer, diabetes, and osteoporosis (Yang et al., 2022). An *in vivo* study has shown that phenolic extracts from blueberry pomace are potent anti-inflammatory compounds, and that the anti-inflammatory effects are mediated by down-regulating the activity of inflammatory markers (*e.g.*, COX-2) (Kunrade et al., 2020). Furthermore, a study by Gu et al. (2020) found that volatile extracts of blueberries and the monoterpenes therein (*e.g.*, linalool, linalool oxide, and α-pinitol) could modulate lipopolysaccharide-induced inflammatory responses in RAW 264.7 cells through inhibition of the nuclear factor-κB (NF-κB) pathway. There is an urgent need for further research to understand how blueberry pomace impacts inflammatory and/or oxidative stress-related cells. Future studies should elucidate whether the phytochemicals present in blueberry pomace exhibit synergistic effects or target distinct molecular pathways. Such research will be crucial for developing targeted therapeutic applications and validating the health benefits attributed to blueberry pomace.

### *3.3. Anti-diabetic effect*

Diabetes is a chronic metabolic disease. By 2045, the number of people suffering from diabetes could reach 6.93 million (Cho et al., 2018). These circumstances indicate that there is an urgent need for appropriate preventive and control measures to curb the rising incidence of diabetes and its related diseases. In this regard, several fruits and their by-products, including blueberries, have recently shown significant hypoglycemic effects due to the presence of antioxidant compounds in the berries (Sun et al., 2020). Clinical data showed that the baseline blood glucose level in mice after overnight fasting was 4.51 ± 0.44 mM. Oral administration of corn starch resulted in a significant increase in blood glucose level, which peaked at 60 min after administration (9.73 ± 1.53 mM) and gradually decreased to the baseline level at 180 min after administration. In contrast, the berry by-product extract significantly inhibited the 30-min elevation of blood glucose after starch administration, suggesting that berry by-product extract is effective and superior to corn starch in alleviating postprandial hyperglycemia (Takács et al., 2020). Studies have demonstrated that polysaccharide-polyphenol conjugates from blueberry by-products (blueberry pomace) exhibit antidiabetic potential by inhibiting α-glucosidase activity (Campos et al., 2021). This polysaccharide-polyphenol conjugate is predominantly found in blueberry pomace and is therefore considered to be a potential natural diabetes therapeutic substance. In addition, five anthocyanin glycosides isolated from rabbit's eye blueberry by-products (*Vaccinium virgatum*), mallowsin derivatives, quercetin-O-hexoside, and caffeic acid have been found to improve glucose intolerance in diabetes mellitus by their ability to inhibit α-glucosidase activity and to cause hepatic lipid accumulation and to increase the expression of genes for renal inflammasomes and KIM-1 (Zhu et al., 2023). In conclusion, plant compounds such as polysaccharide-polyphenol conjugates, anthocyanins, and quercetin in blueberry pomace demonstrate potential effects against diabetes and are expected to be a potential source of novel diabetes therapeutics in the future. However, the specific mechanism of action and evidence of metabolic uptake of these compounds in diabetes therapy are still very limited.

### *3.4. Anti-obesity and hyperlipidemia*

Hyperlipidemia poses a serious threat to human health as one of the major risk factors for vascular diseases. Although many chemical drugs developed by researchers have shown rapid and favorable efficacy in lowering blood lipids, these drugs are often accompanied by side effects. Consequently, there is a considerable interest in identifying harmless active ingredients. The anthocyanin loaded in blueberry pomace has been shown to be a natural small molecule component with good lipid-lowering activity (Cheng et al., 2024). Studies have shown that blueberry anthocyanin nanoparticles made by combining anthocyanin with gum arabic and soy lecithin were able to enhance *in vitro* biocompatibility, uptake capacity, and lipid-lowering activity to varying degrees, and induced an imbalance in the gut microbiota in obese mice (Cheng et al., 2024). Many clinical trials have also demonstrated the positive effects of anthocyanosides on glycemic control, insulin sensitivity and lipids in humans, both anthocyanosides significantly reduced fasting blood glucose (Standardized mean differences (SMD):-0.31; 95 % CI:0.59, −0.04; $I^2$ = 80.7 %), postprandial 2-h blood glucose (SMD:-0.82; 95 % CI:-1.49, −0.15; $I^2$ = 77.7), glycosylated hemoglobin (SMD:-065; 95 % CI:1.00, −0.29; $I^2$ = 72.7 %), total cholesterol (SMD:-0.33; 95 % CI:-0.62, −0.03; $I^2$ = 86.9 %), and low-density lipoprotein (SMD:-0.35; 95 % CI:8.66, −0.05; $I^2$ = 85.2 %)) (Yang et al., 2017). Significant improvements in glycemic control, lipids, cholesterol levels, and biocompatibilitysupport the benefits and potential of anthocyanosides in the prevention and management of hyperlipidemic metabolic diseases. Further well-designed synergistic/antagonistic trials are needed to assess the long-term effects of blueberry pomace anthocyanosises on metabolic profiles and to explore the optimal structure, formulation and dosage.

### *3.5. Improvement of cognitive impairment*

Cognitive impairment is a clinical state conceptualized as a stage between normal cognition and dementia. Currently more than 100 million people worldwide have cognitive problems. Supplementation with blueberries or their extracts reversed memory and cognitive deficits in mice, as tested in mouse models of Alzheimer's disease (Li et al., 2023b). In addition, correcting aberrant neuroplasticity mediated by neuroinflammation by inducing the expression of pro-inflammatory cytokines (IL-1β, TNF-α) has the potential to rescue cognitive deficits (Qiu et al., 2021). The neuroinflammatory inhibitory effect of blueberries and blueberry pomace may depend on anthocyanins, organic acids, minerals and vitamins in blueberries and blueberry pomace (Duan et al., 2022; Kalt et al., 2020; Popović et al., 2022). Currently, however, the evidence for an association between blueberry pomace and cognitive outcomes is somewhat stronger than for individual nutrients and food groups, possibly due to the cumulative beneficial effects of the large amounts of phytocompounds such as anthocyanins, flavonoids, and astragalus found in blueberry pomace. Multi-domain food combined with blueberry pomace interventions (including fish oil, pomegranate, grapes, walnuts, elderberries) may also hold some promise for the prevention of cognitive impairment and dementia, but their effectiveness remains uncertain. Conducting further multidirectory, multicomponent combination assessments, such as those involving fish oil eicosatetraenoic acid (EPA) in conjunction with blueberry pomace anthocyanin, alongside the recent discovery of astragalus, pomegranate, flavonoids, and neurobiological and microbial metabolic outcome biomarkers, is crucial for achieving this objective.

### *3.6. Antimicrobial and improved gut health*

Many antimicrobial agents are currently produced and used for the treatment of human and animal infections, and they are closely related to phenolic compounds. Liu, Wu, et al. (2021) found that anthocyanin showed strong antibacterial activity against *Escherichia coli* and *Listeria monocytogenes*. Blueberry pomace reduced the TBARS count, growth of *Aspergillus niger*, *Bacillus globulus*, *Penicillium flavum* and *Vibrio parahaemolyticus* in samples (Babaoğlu et al., 2022; Sun, Hao, et al., 2020). In addition to this, crude extract of blueberry pomace also showed antibacterial and antifungal activity. The evidence indicates that the active substances in blueberry pomace possess certain antibacterial properties, rendering them a potential source of antibacterial agents with considerable application prospects (Babaoğlu et al., 2022).

Fermented blueberry pomace can also modulate faecal flora by increasing acetic, butyric and lactic acids, making it potentially valuable for improving gut health. It is worth noting that the mechanism of bacterial inhibition regarding the active ingredient in blueberry pomace was performed *in vitro* using specific cell lines. Therefore, these results may not accurately reflect the potential effects of blueberry pomace in other cell types or *in vivo* models. Further studies, particularly *in vivo* studies and investigations into the underlying mechanisms of the observed effects are necessary to obtain a better understanding of blueberry pomace effects and their potential impact on human health (Cheng et al., 2020).

## 4. Bioavailability of active ingredients and its influencing factors in blueberry pomace

Blueberries and blueberry pomace are a rich source of nutrients, fat-soluble bioactives and polyphenols, which should be bioavailable after passing through the different stages of digestion in the gastrointestinal (GI) tract so that they can reach the target organs or tissues that confer their health benefits. In addition, polyphenols are closely associated with nutrients and plant cell wall materials that delay or impede their release from food matrices after mimicking gastrointestinal digestion at different pHs and enzymatic environments. Therefore, the dynamic process of nutrient and polyphenol bioavailability should be considered when evaluating the health benefits of blueberries or blueberry pomace. The bioavailability of nutrients and polyphenols from blueberries and blueberry pomace has been reported in several *in vivo in vitro* models and human studies using simulated gastrointestinal digestion models (Naeem et al., 2022). Therefore, the bioavailability of these nutrients

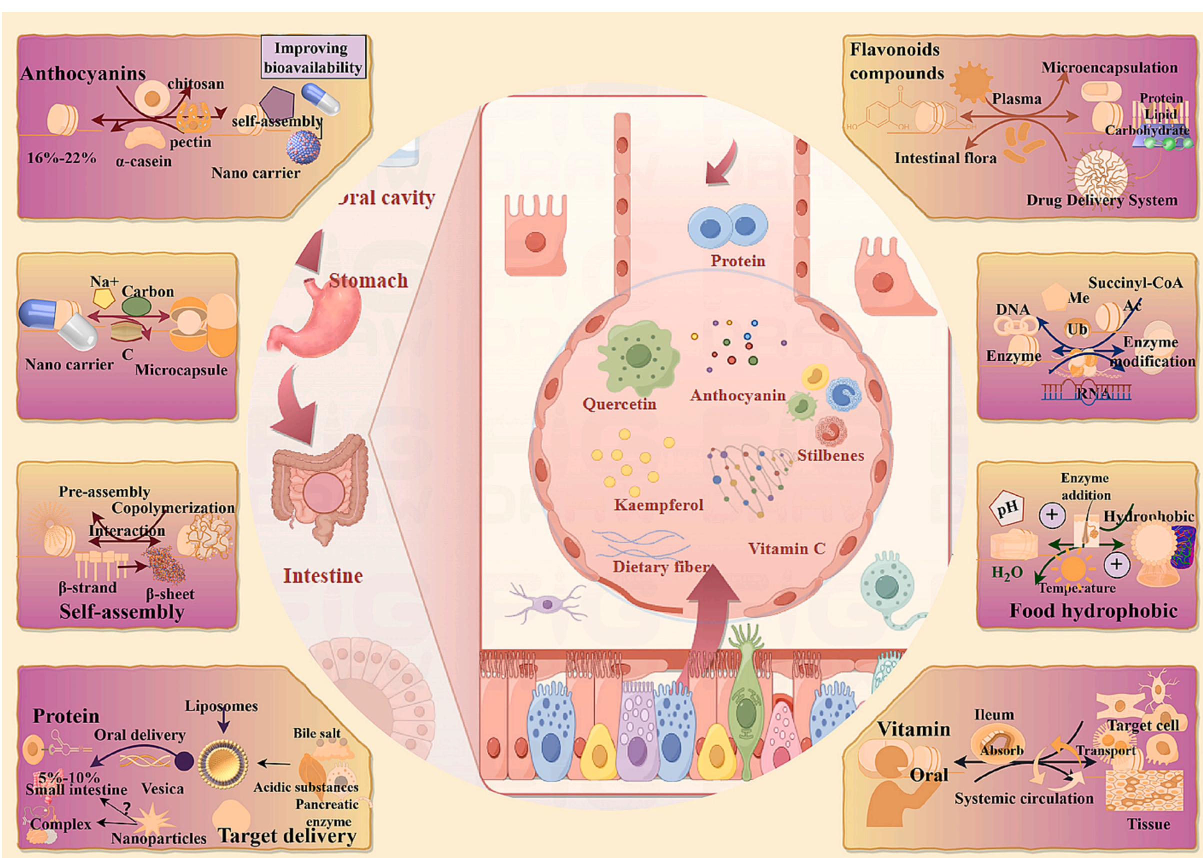


**Fig. 3.** Bioavailability of active ingredients in blueberry pomace (By Figdraw).

and polyphenols is discussed below. Little data are available for other specific active ingredients (*e.g.*, Stilbenes, minerals, sugars, and acids) (Fig. 3).

### 4.1. Anthocyanins

Anthocyanins are extremely hydrophilic and are usually combined with different food sources, and only trace levels can be determined in plasma and urine due to the influence of the food matrix on their absorption. Anthocyanin bioavailability is related to its chemical structure and food source matrix. It has been shown that the bioavailability indices of anthocyanin glycosides all remain low after simulated digestion, all below 16 % (Li et al., 2024). For this reason, scholars conduct various studies to improve the utilization of anthocyanins. For example, Xie et al. (2023) constructed nanocarriers for anthocyanins (CS-ANCs-PC) by electrostatic self-assembly using chitosan and olive pectin. Compared with free anthocyanins, CS-ANCs-PC not only enhanced *in vitro* digestibility but also had better DPPH and OH scavenging activities. However, α-casein was found to be a potentially more potent enhancement of blueberry-derived anthocyanin utilization substances. Lang et al. (2023) analyzed the effect of α-casein on the excretion of blueberry-derived anthocyanins in urine and feces using α-casein as a vehicle through a rat model, and found that α-casein inhibited the degradation of blueberry-derived anthocyanins. It suggests that α-casein can effectively control the excretion of blueberry-derived anthocyanin metabolites and help more blueberry-derived anthocyanins and their metabolites to enter the blood circulation.

### 4.2. Flavonoids

Flavonoids are a class of insoluble compounds found in berries, including kaempferol, quercetin and poplin. These substances have antioxidant, anticancer and antimicrobial properties and protect against cardiovascular disease. Flavonoids in berries are bioavailable, such as quercetin. One clinical trial showed a 50 % increase in plasma quercetin levels when subjects consumed 100 g of lingonberries, lingonberries, and blackcurrants per day for two consecutive months. Most other flavonoids are recovered in the plasma due to their small molecular weight, and some flavonoids have two absorption peaks, suggesting that reabsorption of compounds eliminated in the bile or high molecular weight metabolism is not absorbed in the stomach by the intestinal flora. Currently, one of the ways to improve the bioavailability of flavonoids is to microencapsulate them. Hu et al. (2018) used gum arabic (GA)-stabilized emulsions and microcapsules to encapsulate flavonoids extracted from citrus peels and found that the microcapsules showed enhanced ability to protect the flavonoids from degradation and control their antioxidant capacity. Another approach to increase the bioavailability of flavonoids is the use of nanostructure-based drug delivery systems such as protein, carbohydrate, and lipid carriers (Cai et al., 2018). These carriers increase the bioavailability of flavonoids at specific sites by preventing degradation in the gut, leading to higher concentrations. Relatively few studies have been reported on the plasma or intestinal digestion and absorption of flavonoids from blueberry sources. This may be because less attention has been paid to flavonoids in blueberries or their bioavailability has been affected by other factors. Future studies could further explore the bioactivity and absorption mechanisms of flavonoids in blueberries to better understand their potential benefits to human health.

### 4.3. Proteins

Protein-based drugs share common physicochemical properties such as high molecular weight, hydrophilicity and enzyme/pH sensitivity. In recent years, the development of oral administration of peptides/proteins as a non-invasive therapeutic approach has emerged as an attractive alternative to the parenteral gastrointestinal route, considering long-term administration, safety, convenience, less pain and less healthcare cost burden. It is the most favorable method of drug delivery, especially for the treatment of chronic diseases such as diabetes mellitus and hepatitis B, which require long-term drug administration. Several efforts have been made in recent years for oral delivery of therapeutic peptides/proteins and some of the promising peptide/protein oral drug delivery systems are in clinical trials. Furthermore, Chima et al. (2022) evaluated the effect of blueberry complexes on protein digestion *in vitro* and found that consumption of these compounds did not necessarily translate into their delivery to body tissues, with only about 5–10 % being absorbed in the small intestine. Currently, the lack of information on the detailed absorption mechanisms of established delivery systems *in vivo* is a major obstacle to further research progress. More mechanistic studies are needed to reveal the details of intestinal absorption of nanoparticles for rational nanoparticle design and improved oral bioavailability. In conclusion, these new delivery systems pave a new way for oral delivery of therapeutic peptides/proteins.

### 4.4. Vitamins

Vitamins assist in chemical reactions in the body and are important for cell membrane integrity, nerve and muscle function, bone formation, as well as normal growth and overall good function of the body. Although most vitamins are widely distributed in foods, vitamin deficiencies are common in the population and may occur even in the presence of apparently adequate dietary intake. This may be attributed to the under-absorption and under-utilization of vitamins present in the human diet (Chungchunlam & Moughan, 2023). Several studies have estimated the availability and utilization of vitamin C in vegetables and fruits. Currently, most of the studies on the *in vivo* bioavailability of vitamins from berries have focused on guava and kiwifruit, and research on other berries and their by-products, especially blueberries, remains urgent. In addition, the bioavailability of vitamins is highly variable among dietary sources, and further studies are needed to determine the bioavailability of some important vitamins in foods, especially blueberries and their processing by-products, which are rich in vitamin C. At the same time, the bioavailability of vitamins in the context of mixed or whole diets is an important consideration, but there are limited data on the bioavailability of vitamins in mixed diets, especially mixed diets of blueberries and their processing by-products (Chungchunlam & Moughan, 2023).

## 5. Blueberry pomace in food application

In recent years, the utilization of by-products of agricultural product processing has received increasing attention. On the one hand, it is conducive to environmental protection, and on the other hand, it can increase the comprehensive utilization and added value of by-products. As an important by-product, blueberry pomace has also attracted the attention of many researchers and gained more and more applications (Li et al., 2021). Therefore, this section summarizes the potential of blueberries and their by-products in food-related applications (Fig. 4).

### 5.1. Dairy products and fermented beverages

Food spoilage is associated with oxidation. At the same time, oxidative reactions produce free radicals associated with various diseases such as cancer, diabetes, cardiovascular disease and inflammation, posing a serious threat to the health of consumers. Therefore, there is a need to prevent the production of free radicals in food. Blueberry pomace contains a large amount of antioxidant phenolics, and it is economically feasible and environmentally friendly to use blueberry pomace as raw material for dairy products and fermented blueberry pomace beverages produced by suspension, filtration, clarification, and combined with milk and probiotic fermentation processes (Chima et al., 2022).

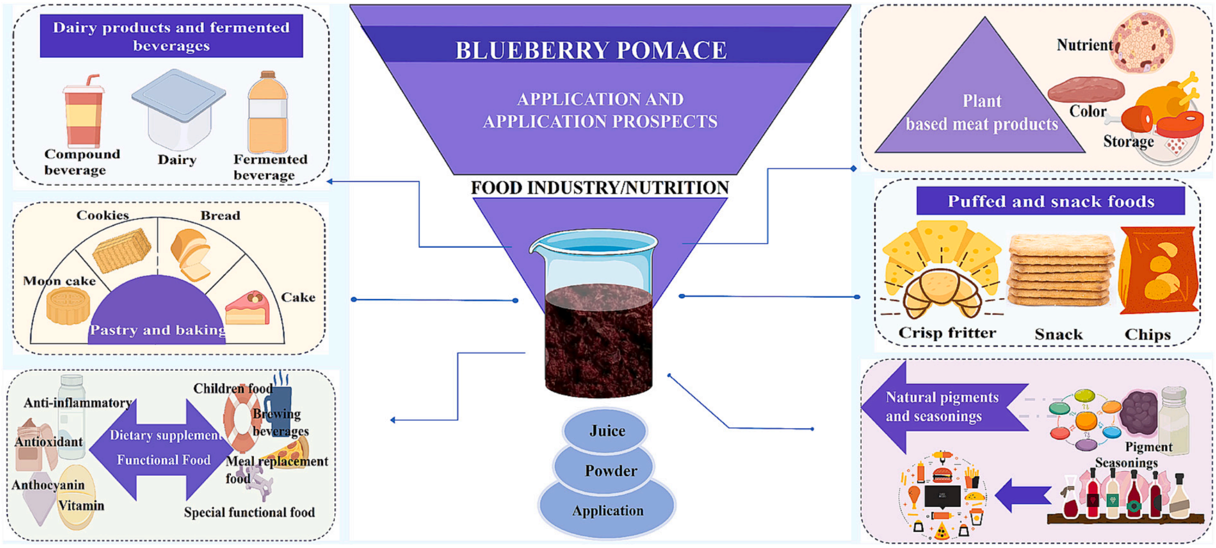


**Fig. 4.** Blueberry pomace applications and application prospect in food industry.

Since blueberry pomace contains small amounts of protein and ash, it can be enriched by lactic acid bacteria fermentation. In a study based on the production capacity of blueberry polyphenol-bound cannabis complexes, the physical and chemical properties of each protein extract were compared in the presence and absence of blueberry polyphenols. Hemp and pea proteins appeared to be the ones with greater polyphenol binding affinity than whey, possibly due to the observed differences in protein secondary structure. When exploring the effects of plant proteins on phytochemical function in complex "whole food" matrices, while an increase in turbidity was observed for plant-based proteins at all pH levels with the addition of blueberry polyphenols, no significant increase in turbidity was observed for pea and hemp after the introduction of blueberry polyphenols into whey proteins at pH 2.0 and 4.6, which would enhance their ability to increase polyphenol bioavailability (Chima et al., 2022).

Blueberry pomace fermented beverages can be dairy or non-dairy depending on whether a dairy source is added. Microbiological screening is performed after first fortifying the chemical composition of the blueberry pomace, which ensures the quality and safety of the pomace before it is used in the production of the fortified fermented beverage. Fermented beverage production followed. For example, different amounts of blueberry pomace (2 g, 4 g, 6 g, 8 g, and 10 g/100 g) were added to sterile containers, where the blueberry pomace chemical composition contained 0.5 g/100 g fat, 87 g/100 g carbohydrates, 5 g/100 g fiber, and 0.2 g/100 g protein. Inoculated blueberry pomace was separated therein, mixed, and incubated at a constant temperature of 35 ± 1 °C until the pH of the samples reached 4.6 ± 0.1 (9 h). The blueberry pomace samples were refrigerated at 4 °C (Trajkovska et al., 2024). In addition, the three-dimensional gel network of blueberry pomace fermented beverages protects probiotic strains during digestion and consequently increases their bioaccessibility. It has a promising application as a main ingredient in dairy products and fermented beverages.

### 5.2. Pastry and bakery products

Blueberry pomace can be used in pastry and bakery products because it is rich in dietary fiber that improves water retention and maintains a good crunchy texture. The high-water retention capacity of the fiber is related to the high number of hydroxyl groups capable of forming hydrogen bonds with water molecules. Another mechanism of water retention is the migration of water in the fiber capillary structure due to surface tension. Berry fiber concentrates have similar fiber content, but differences in their water absorption capacity are mainly attributed to differences in fiber distribution, structural characteristics, and chemical composition (Šaric et al., 2018). The current study showed that when 4 % blueberry pomace was added to the dough, it not only reduced the final viscosity and setting value of the low gluten dough, but also altered the water absorption, textural properties, and color difference of the dough (Liu et al., 2023). Many studies have reported that the addition of dietary fiber to baked goods results in poor dough processability and significantly alters the quality of the final product (Šaric et al., 2018). The addition of raspberry and blueberry fiber concentrates to cookies by Šaric et al. (2018) made them candidates with high-fiber nutrients and greater crispness. Since water and fat, as the main components associated with the dough processability and baking quality of the product, were added in the same amounts in all formulations, the differences between cookies can be attributed solely to the content and functional properties of the added fiber concentrates. The high content of dietary fibers in blueberry fiber concentrates, their high-water absorption capacity, and their ability to bind water through hydrogen bonding resulted in less free water being retained in the system, which resulted in limited water mobility and availability to the other components (hydrocolloids and starch), and in the production of drier, stiffer doughs. These studies imply that blueberry pomace can be used as an additive to improve the nutrition and texture of food products, and may provide a theoretical reference for value-added applications of blueberry pomace in pasta products.

### 5.3. Nutritional supplements and functional foods

Recent trends in the food industry indicate that dietary supplements and functional foods are gaining popularity around the world and they are becoming part of the daily diet in developed countries. Currently, blueberry pomace is used as a supplement to prevent and reduce the complexity of age-related diseases and to improve learning and memory in children (Tran & Tran, 2021). It is highly active in stopping biological damage to neuronal function. This is because the brain may be more susceptible to oxidative stress than other organs, resulting in lower activity of its antioxidant defense system. Therefore, blueberries as nutritional supplements should be a direction for a new industry in the future. In addition, to assess the effect of blueberries and raspberries on certain factors strongly associated with cardiometabolic risk (lipid status, fasting glucose and lipocalin levels), as well as on liver and kidney function and anthropometrically measured biomarkers. Popović et al. (2022) utilized blueberry and raspberry pomace in place of 30 % of gluten-free flour incorporated into gluten-free cookies designed as a functional food. The study included 20 healthy women, aged 30–50 years (41.35 ± 8.58 years). During the consumption of functional foods with blueberry components, their lipoprotein cholesterol levels decreased by 20.16 %. However, the process of how blueberry pomace utilizes its own constituents to exert its role as a functional product that may contribute to the prevention of atherosclerosis is not clear. Therefore, the use of blueberry pomace, a by-product of the food industry, for the development of other industrial chains is in line with the needs of the circular bio-economy and the protection of health interests of the population.

### 5.4. Plant-based meat products

Reduced reliance on animal-based diets for nutritional and environmental reasons is driving market demand for a new generation of sustainable plant-based meat alternatives. Blueberry pomace can be used as a natural additive in plant-based meat products to provide color and additional nutrients while enhancing the product's healthy image. For example, the pigments in the matrix obtained from black beans by adding blueberry pomace during the storage and fermentation process of soy products show better stability, while the nutritional value will be higher (Ścibisz & Ziarno, 2023). Furthermore, plant-based foods are marketed as having a low carbon footprint, and a significant challenge for the future lies in researching and refining the blends used in the production of plant-based artificial meat, as well as optimizing the manufacturing process.

### 5.5. Puffed food and leisure food

Puffed food is starchy raw materials processed by extruding, deep-frying, microwaving, baking and other different puffing techniques. As a kind of leisure food, puffed food is favored by consumers, especially children and teenagers, worldwide because of its crispy taste, beautiful appearance and easy to carry and eat. Although puffed technology has a history of many years, many food research experts and food companies are still enthusiastic about its research in recent years, hoping to explore new production processes and produce more new puffed foods to meet market demand. Utilizing the by-product fruit residue produced after blueberry pressing, the development of a new type of leisure food into a treasure will enhance the comprehensive benefits of the blueberry processing industry. In order to develop new leisure food products, Nakov et al. (2020) added 4 % grape pomace powder combined with wheat flour to make cakes and showed that the pomace significantly increased the content of highly bioavailable free phenols, which are deficient in bakery wheats, and consequently increased the nutritional value and nutritional enhancement properties of the cakes without compromising their technical and sensory attributes. In addition, grape pomace provided several phenolic substances such as catechin, gallic acid, quercetin, protocatechuic acid, kaempferol and apigenin. The content of phenolic acids and flavonoids in the cake also increased to 26.4–60.9 mg/kg.Therefore, the use of blueberry pomace to produce extruded puffed food is an innovative application.

### 5.6. Natural colors and flavors

Color is an important sensory attribute of food products and often plays an important role in the market success of the product. Consumers often use color as an indicator of various qualities of food such as flavor, safety, and nutritional value. Since blueberry pomace contains natural pigments, it can be used as a natural food coloring to provide attractive color to candies, pastries and other food products. Wang et al. (2024) found that the (−)-epigallocatechin gallate accessory pigment anthocyanin exhibited high absorbance (0.34 a.u.) and redness (27.09 ± 0.17) in a model of blueberry fermented beverage. The blueberry fermented beverage aged for 90 days showed high absorbance (1.02 a.u.), percentage of polymerised color (PC%, 68.3 %) and good color saturation (*, 43.28) and contained more mallotannin-3-glucoside. Blueberries are of great interest as a natural source of color in the food, cosmetic and pharmaceutical industries. The use of natural sources of pigments as food colorants is a challenging process and varies depending on the type of pigment and the specific application. To achieve the various colorimetric properties and stability of synthetic food colorants, it is necessary to draw inspiration from the mechanisms that occur in natural systems.

The natural flavors in the pomace can provide a unique flavor to sugar-free chewing gum or candy. Methods of encapsulation, for example, along mixtures of flavors and sweeteners. Flavor-masking medicated chewing gums provide a palatable medication and dietary supplement for children and the elderly. Traditionally, flavor-masking medicines are prepared in a slow-release formulation. It provides sustained release of drug after normal chewing time (15–30 min). However, because continuous chewing may lead to TMJ disorders. As a result, new medicinal chewing gums are being developed for use in various medications, which have a fast onset of action, pleasant flavor, and high bioavailability. In the future, the pharmaceutical industry is expected to produce more about medicinal blueberry flavored chewing gums to treat other conditions to improve people's diseases.

## 6. Conclusions and challenges

Blueberry pomace is abundant in bioactive compounds, including polyphenols, dietary fiber, and essential minerals. However, the instability and low bioavailability of these compounds pose challenges for their utilization, which may also present opportunities for further research into their biological effects. This paper summarizes the progress of research on the extraction of active components of blueberry pomace and their biological activities in recent years. Blueberry pomace is one of the valuable sources of dietary fiber, total sugars, vitamins and minerals in the future, but there are fewer studies and more immature methods for the isolation and extraction of these substances from blueberry pomace. The active ingredients extracted from blueberry pomace have beneficial effects on human health, including antioxidant, antidiabetic, anticancer, anti-inflammatory and antimicrobial properties. There is also a great potential for applications in the food industry, such as functional beverages, nutritious snack products, botanical meat products, natural colors and flavors. However, *in vivo* bioavailability studies of these active ingredients in the host are imminent. Meanwhile, more evidence such as the mechanism of action of phenolic compounds such as flavonols and chlorogenic acid is needed to confirm the promotive effect of blueberry pomace on intestinal health to enhance its application. In conclusion, blueberry pomace is regarded as a promising substance for functional food applications due to its bioactive components with various functional properties. In addition, there are still many limitations in the research on the biological effects of blueberry pomace. For example, research on the bioactive compounds in blueberry pomace has primarily focused on their effects on phenotypic alterations and gene expression in various species, and little is known about the molecular mechanisms by which these compounds regulate intracellular signaling pathways. In addition, can we explore what are the mechanisms of bioavailability and cellular uptake of active ingredients in blueberry pomace? How can we maximize the application and added value of blueberry pomace in the food industry? These questions are at an unexplored stage in infancy. Besides, there are few high value-added products with clear health care functions and the industrial chain is not perfect. These issues will be a concern in future research and need to be explored in further studies.

## CRediT authorship contribution statement

**Tianyu Huang:** Writing – original draft. **Yu Zhang:** Methodology. **Linxiang Qiao:** Data curation. **Donglan Luo:** Formal analysis. **Liangjie Ba:** Resources. **Su Xu:** Software. **Lingshuai Meng:** Resources. **Sen Cao:**

Writing – original draft. **Tao Wang:** Funding acquisition. **Xiaohong Kou:** Supervision.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Data availability

No data was used for the research described in the article.

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