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Berries as Foods: Processing, Products, and Health Implications

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Abstract

Berries are highly regarded as flavorful and healthy fruits that may prevent or delay some chronic diseases attributed to oxidative stress and inflammation. Berries are low in calories and harbor diverse bioactive phytochemicals, antioxidants, dietary fibers, and vitamins. This review delves into the main characteristics of fresh berries and berry products as foods and the technologies associated with their production. The main effects of processing operations and related variables on bioactive components and antioxidants are described. This review critically discusses why some health claims based on in vitro antioxidant data and clinical studies and intervention trials are difficult to assess. The review suggests that the beneficial health effects of berries are derived from a multifactorial combination of complex mixtures of abundant phenolic components, antioxidants, and their metabolites acting synergistically or additively with other nutrients like fibers and vitamins and possibly by modulating the gut microbiota.

INTRODUCTION

NCDs: noncommunicable diseases

CVDs: cardiovascular diseases

BACs: bioactive compounds

TPCs: total polyphenolic compounds

RONS: reactive oxygen and nitrogen species

Edible berries comprise true berries that have a fleshy center covered with a skin (e.g., blueberry and cranberry), those composed of aggregated fleshy drupelets (e.g., blackberry and raspberry), and strawberries, where the true fruits (achenes) are on the outside of a fleshy receptacle (Aguilera & Toledo 2022). "Berries" in this article refers to the small, soft, and colored fruits of the genera *Fragaria* (strawberries), *Vaccinium* (blueberries, cranberries, and bilberries), *Rubus* (raspberries, blackberries, and cloudberries), *Ribes* (several species of gooseberries and black and red currants), *Aronia* (chokeberries), and *Sambucus* (elderberries). Most of these berries are cultivated, but hundreds of edible wild berry species around the world are consumed by local people (Aguilera & Toledo 2022, Padmanabhan et al. 2016).

Berries enjoy ample popularity among consumers because of their unique flavor, versatility, ease of consumption, and potential health benefits. Thus, the year-round local production and international trade of fresh berries increased significantly in the past two decades. Allegedly, berries may prevent or delay noncommunicable diseases (NCDs) attributed to oxidative stress and inflammation, for example, cognitive impairment and dementia, some types of cancer, and cardiovascular diseases (CVDs), as well as frailty of the immune system (Govers et al. 2018, Liguori et al. 2018, Zorzi et al. 2020). In addition, the consumption of berries may reduce the risk of type-2 diabetes, improve weight maintenance, and provide neuroprotection (Kalt et al. 2020).

Berries are recognized for their high content of bioactive compounds (BACs) that are not essential to meet basic nutritional needs but may convey health benefits. BACs in berries are ambiguously defined, but, in general, they include several phenolic compounds (e.g., phenolic acids, anthocyanins, and flavonols) with high antioxidant activity and other potential health bioactivities and may or may not include ascorbic acid (vitamin C) and minor antioxidants (Battino et al. 2009, Manganaris et al. 2014, Nile & Park 2014, Shahidi & Ambigaipalan 2015, Skrovankova et al. 2015). In this review, the term BACs is mostly used in its extended meaning.

Berries are important sources of BACs, although there is a substantial variation in the profile and concentration of total polyphenolic compounds (TPCs) among and within berry populations due to genetics, environmental factors, maturity stage, and storage conditions (Di Vittori et al. 2018, Karlund et al. 2014). Several berries contain high levels of vitamin C and are excellent sources of folate (vitamin B9), vitamin E, and vitamin K (Golovinskaia & Wang 2021). Berries are rich in total dietary fibers, but the proportion of soluble dietary fibers (associated with reduction of the glycemic response and plasma cholesterol) may not exceed 10–12% of the total fiber content (Alba et al. 2019). Glucose and fructose are the predominant sugars in berry fruits, and malic acid and citric acid are the major organic acids (Mikulic-Petkovsek et al. 2012).

Elevated levels of highly oxidant molecules called free radicals, including reactive oxygen and nitrogen species (RONS), can damage proteins, lipids, and DNA in our cells. Under normal physiological conditions, our endogenous antioxidant defense systems probably compensate for excess free radicals (Liguori et al. 2018, Nwachukwu et al. 2021). Some clinical studies have shown the potential protective effects of berries in controlling the risk of NCDs caused by endogenous oxidative damage and inflammatory responses (Foito et al. 2018, Yang & Kortesniemi 2015). Because berries have a high concentration of antioxidants, it is hypothesized that the protective action of berries is mainly derived from the neutralization of the deleterious effects of RONS by these exogenous antioxidants (Silva et al. 2020).

Although the agronomic, chemical, and health aspects of berries are well reported, their processing and utilization as fresh foods, food products and beverages, ingredients, and culinary products have received less attention in the food science literature (Beattie et al. 2005, Debelo et al. 2020, Golovinskaia & Wang 2021, Nile & Park 2014, Pap et al. 2021). This is unfortunate because these small fruits come onto our tables in many edible forms deploying nutritional and sensorial properties appreciated by consumers (Bhat et al. 2015, Karlund et al. 2014). Thus, the main objectives of this article are to (*a*) describe important uses of berries as foods and traditional and novel processing technologies leading to their utilization; (*b*) provide a contextual and critical overview of the significance of in vitro analyses of antioxidants and clinical studies related to the invoked health benefits of berries; and (*c*) report on the influences of storage and processing on the content of BACs and the quality of berries.

MMT: million metric tons

BERRIES AS FOODS

Consumers' Demands and Preferences

Nutritional recommendations advise incorporating fruits as part of a healthy diet. Fresh berries are convenient alternatives because they are amply available and easy to portion, require no peeling or cutting, and generate almost no waste. The 12.2 million metric tons (MMT) of berries and currants produced globally in 2019 doubled the production of 2005, assisted by a counter-seasonal supply from the Southern Hemisphere. However, consumers do not equally demand all types of berries. Strawberries (~9 MMT/year) are preferred in China and the United States. Strawberries are followed at a distance by raspberries and blueberries, whose global yearly production more than doubled between 2010 and 2019 to nearly 1.0 MMT (FAOSTAT 2021). The global berry market was valued at US$826 billion in 2020 and is expected to grow at an annual rate of 6.8%. Demand for organic fruit is expanding fast in the United States and Europe, and some emerging countries are becoming important producers and exporters of organic berries to these markets (Fortune Bus. Insights 2020).

Texture, sweetness, and aroma are desirable organoleptic properties of most berries. Surveys reveal that preference for berries and berry products varies among countries, with locally produced fresh fruits ranking high. In the United States, sweetness and intense flavor, but not sourness, are positive purchase traits for strawberries and blueberries (Gilbert et al. 2014). German consumers prefer fresh strawberries with uniform color, good visual appeal, intense fruity aroma, and moderate juiciness (Bhat et al. 2015). Finnish consumers like most berries that are sweet and not bitter, like strawberries, bilberries, and raspberries (Laaksonen et al. 2016). The French are avid consumers of fresh berries, jams, and dairy products containing berries (Popa et al. 2017). Factors that are increasingly taken into consideration in purchasing decisions regarding berries are good agricultural practices, organic cultivation, low food miles (e.g., local versus imported produce), and country/region of origin (Farruggia et al. 2016).

Safety Aspects

Fresh and frozen berries are occasionally involved in foodborne disease outbreaks. Human viruses (i.e., noroviruses and hepatitis A virus) are important sources of foodborne contamination and responsible for most outbreaks in fresh and frozen berries, whereas bacteria (e.g., *Listeria monocytogenes*) may proliferate during postharvest storage (Bozkurt et al. 2021, Oliveira et al. 2019). Although the number of disease outbreaks due to berry consumption is small, fruit producers and processors should ensure a safe microbiological quality along the supply chain.

PROCESSING AND PRODUCTS

People have enjoyed fresh berries since ancestral times. Their short seasonality and limited shelf-life led to the development of several artisanal techniques that prolonged their utilization and consumption (Zhao 2007). Eventually, traditional techniques and culinary uses evolved into processing technologies and products with an extended shelf life. **Figure 1** depicts the major

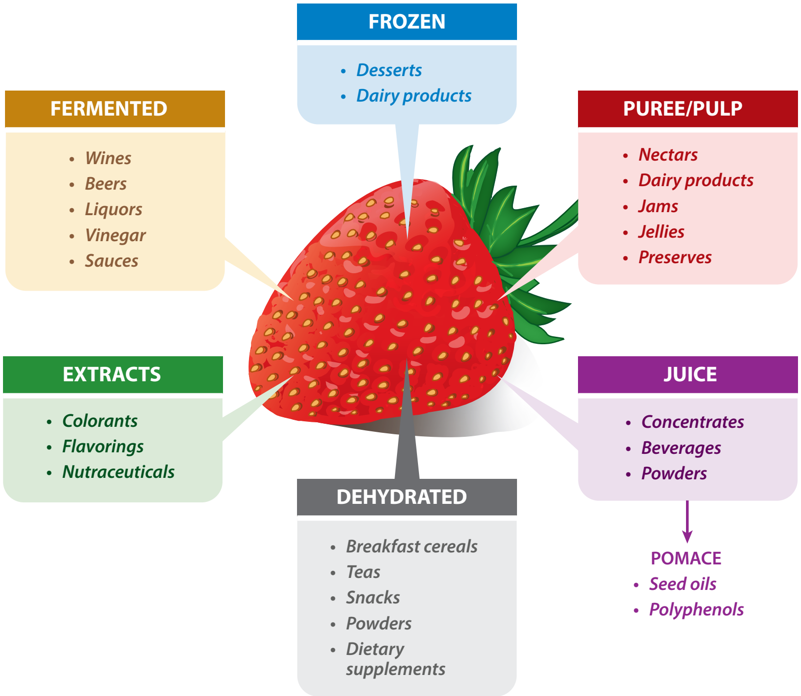

Figure 1

Major categories of commercial berry products. Product applications are depicted in italics.

categories of berry products and some commercial applications such as food products and beverages present in the market today.

Frozen Berries

Freezing is an important commercial process for the long-term preservation, storage, and transportation of ripe berry fruits, providing a steady supply for consumers and the food industry. Fast freezing at low temperatures rapidly immobilizes a large portion of water as ice, thus minimizing cell damage and retarding most deleterious chemical and biochemical reactions. The most utilized equipment to freeze berries is air-blast, impingement, and fluidized bed freezers as well as cryogenic freezers using liquid nitrogen or liquid carbon dioxide. Freezing rate (i.e., the temperature drop inside a product per unit of time) plays a major role in the eating quality of berries. Slow freezing rates (e.g., like those in a domestic freezer) result in large intercellular ice crystals that damage the cell walls and lead to a softer texture and drip loss after thawing (Celli et al. 2015). Due to their small size, berries are especially suitable for individually quick freezing (IQF), which involves spraying cryogenic liquids while circulating the berries on a belt and is completed in a few minutes (Žlabur et al. 2021). Frozen storage ($<$18°C) is required until consumption or processing.

IQF: individually quick freezing

Dehydrated Berries and Powders

Removal of water (dehydration) prolongs the shelf life of berries but induces significant structural and functional changes that severely limit the applications of the final dried products (Aguilera et al. 2003). Solar drying, hot air-drying, freeze-drying, and spray-drying are common methods for dehydrating berries, juices, and extracts (Ravichandran & Krishnaswamy 2021). Dehydrated berries are important components of sweet cakes, breakfast cereals, snacks, backpacking foods, and fruit bars. Berry powders bring natural flavors, attractive colors, and sweetness to instant desserts, sauces, and juices, allowing for clean labels. They are also used in health supplements sold as pills and capsules.

Juices and Related Products

Juices are advantageous alternatives to compensate for the declining consumption of whole fresh fruits and utilize lower-grade raw materials. Consumers appreciate juices of berry fruits for their sweetness, rich flavors, and antioxidant content (AC) (Carpéné et al. 2019). Berry juices have found applications in yogurts and other fermented milks to complement their probiotic effects with antioxidant activity (Dimitrellou et al. 2020).

The manufacture of berry juices is covered in detail by Leong & Oey (2017). It involves blanching and physical disruption of the fresh or frozen fruit into a mash that contains solutes, natural pigments, cell wall material, skins, and seeds. Enzymatic treatment of the mash is often utilized to increase the juice yield and release bioactive components from the cellular matrix (Bender et al. 2017, Karlund et al. 2014). Pressing of the mash produces a cloudy juice that is further clarified to remove suspended colloidal particles and pectin. Most commercial berry juices undergo pasteurization or aseptic packaging to eliminate pathogenic microorganisms and inactivate quality-degrading enzymes. Berry juice processing leaves large quantities of pomace or press-cake that retain a substantial amount of BACs in the skins and seeds (Struck et al. 2016).

The distinction between concentrates, purees, and pulps is diffuse and depends on manufacturing and applications. Concentrates are commodities produced by reducing the water content of juices by evaporation or reverse osmosis to increase the total solids content and the viscosity, thus saving in storage and transport costs (Lozano 2006). Fruit purées and pulps are semifinished, intermediate products obtained by grinding, milling, and sieving the edible part of the fruit without removing the juice. A variety of commercial products, including jams, nectars, baby foods, dairy products, conserves, and salad dressings, use berry concentrates, purees, and pulps to provide flavor, color, and nutrients. Strawberry leathers, made by dehydrating a thin layer of fruit puree mixed with additives, are consumed as shelf-stable snacks (Diamante et al. 2014).

Jams and Jellies

Jams, jellies, and preserves are popular berry products stable at room temperature because of their high content of soluble solids (mainly added sugar). Jams typically contain fruit pieces or crushed fruit, jellies are produced with the juice extracted from the fruit, and preserves are generally made from whole berries. Jams are prepared by cooking fruits with sugar to a soluble solids content of over 65% and usually have added pectin (to increase the viscosity and promote gel formation) and citric acid (as a preservative) (Garden-Robinson 2020, Shinwari & Rao 2018). Boiling of the fruits breaks down the cellular structure—releasing polysaccharides and flavor compounds—evaporates some of the water, and provides a pasteurization effect.

Among traditional and regional products are berry jams, jellies, and compotes, as well as kissel, a classical dessert in Northern Europe consisting of the sweetened juice of berries thickened or gelled with starch. Commercial dairy products (e.g., yogurts, fermented milks, and desserts) containing berry pulps and jams exploit the health benefits associated with these fruits (Dimitrellou et al. 2020).

Infusions, Nonalcoholic Beverages, and Extracts

Infusions and "teas" from dried berry fruits have gained popularity for their fragrance, flavor, and alleged therapeutic benefits. Traditional medicine recommends infusions and decoctions of various berry fruits to treat several diseases, including common colds, inflammation, diabetes, and ocular dysfunction. Berry fruit teas tend to have higher contents of flavonoids and anthocyanins than herbal teas and commercial fruit teabags and are often a mixture of dried fruit, leaves, and flowers (Šavikin et al. 2014). Brewing conditions, particularly water temperature and brewing time, influence the extraction of antioxidants, colorants, and flavors (İlyasoğlu & Arpa 2017).

Kombucha is an ancestral beverage made by the symbiotic fermentation of sweetened tea by yeast and bacteria. Recently, berry kombucha has become part of the fast-growing functional beverage market that offers health benefits with a low calorie content (Kim & Adhikari 2020). Some berry kombuchas exhibit higher antioxidant activity than their infusions but lower in vitro total phenolic content and antioxidant capacity than black tea kombucha (Abuduaibifu & Tamer 2019).

Most berry extracts are formulated as nutraceuticals with high BACs and AC (Li et al. 2017). There is mounting research activity on berry extracts as natural antioxidants, antimicrobial agents, and colorants for total or partial replacement of their synthetic counterparts in foods. Extracts from several berries act as antioxidants in meats and meat products due to the abundant phenolic compounds (Lorenzo et al. 2018). Berry extracts from blueberries and cranberries have demonstrated inhibitory effects against pathogenic bacteria (Suriyaprom et al. 2022). Naturally derived pigments from berries are safe, clean label, and healthy ingredients; however, their poor stability to pH and temperature limits commercial applications (Gonzalez de Mejia et al. 2020).

Alcoholic Beverages

Fruit wine is the generic denomination of fermented fruit juices. Their production resembles the fermentation of grape wine and cider (Velic et al. 2018). The majority of berry wines in Europe come from blackberries, blackcurrants, raspberries, strawberries, and blueberries. Usually, the total sugar content of berries is low and becomes further diluted in the must when adjusting for acidity, so sugar is added to the must (chaptalization) to achieve an alcohol level of 10–12% during fermentation (Maksimović & Maksimović 2017). To increase consumer appeal, some berry wines may be artificially carbonated.

Beers with special characteristics (e.g., added flavors and medicinal principles) are gaining popularity in several markets. The addition of berries to beers reduces bitterness and gives a balanced sensory profile between the fruit and the original beer base (Brew. Assoc. 2022). In Belgium, there is a long tradition of fermenting some beers with cherry, strawberry, or raspberry fruits, adding new flavors, increasing the BAC content, and providing protection against oxidation.

A fruit spirit is produced by ethanol fermentation of fleshy fruits or a must to give an aroma and taste characteristic of the raw material after distillation. The minimum ethanol content in fruit spirits is 37.5% by volume. Some berry brandies that are well appreciated by consumers are produced from quince, raspberry, blackberry, cornel berry, currant, and blueberry (López et al. 2017). Liqueurs, on the other hand, are sweetened and flavored grain spirits that contain 35–45% ethanol (Śliwińska et al. 2015). Gin is a liquor made from purified spirits and uses the juniper berry as its main flavoring ingredient. The tasteful crème de cassis liqueur made in Burgundy consists of a neutral grain spirit infused with crushed blackcurrants. As a result, it has tart berry flavors with a hint of spice that attracts locals and foreigners alike (Gibot-Leclerc & Gallaud 2010).

Other Fermented Products

Exotic flavors, touted health benefits, prolonged shelf life with clean labels, and microbial safety drive research and development of novel fermented fruit-based products (Kesa et al. 2021). Lactic acid–fermented fruit juices, also called lactojuices, have found consumer acceptance as healthy and refreshing alternatives to fermented milk drinks. Lactic acid–fermented berry juices combine the health benefits ascribed to berries and the probiotic effects of lactic acid bacteria (Szutowska 2020).

d.b.: dry basis

Berries and Gastronomy

Berries have a long gastronomic tradition as desserts and side dishes, baked and confectionery products, ice cream, juices, and liquors (Hibler 2010). Berries recently acquired a renewed notoriety in the gastronomic world as synonymous with great flavor, freshness, new aesthetics, closeness to nature, and healthy lifestyles. Interest in wild berries started at the beginning of this century motivated by a search for novel ingredients, new gastronomic experiences, and healthy eating (Aguilera & Toledo 2022). Presently, local foragers gather and supply wild berries to the restaurant trade (Luczaj et al. 2012). New culinary applications may exploit the natural sweetness, colors, and flavors of these fruits to replace sugar and artificial additives in desserts (Alija & Talens 2012).

Nutraceuticals

Nutraceuticals are food products that provide medical or health benefits, including the prevention and/or treatment of a disease. Berry nutraceuticals loaded with polyphenols and anthocyanins have been extensively marketed for many years, particularly on the Internet (Espín et al. 2007). Novel food nanotechnologies (e.g., nanoemulsification, liposomes, and solid lipid nanoparticulation) may provide enhanced stability, bioavailability, and therapeutic efficacy to the extracted active compounds (Forbes-Hernandez 2020, Tsiaka et al. 2022). Nevertheless, Da Costa (2017) is quite skeptical about the scientific evidence of the efficacy of commercial nutraceuticals and whether they play a role in health, aside from considerations regarding their safety and authenticity (Salo et al. 2021).

Valorization of By-Products from Berry Processing

Berry processing generates by-products with valuable components for the food industry. Their recovery and refinement into commercial ingredients such as antioxidants, antimicrobials, prebiotics, flavorings, colorants, and texturizers (e.g., crude fiber and pectin) may not only be profitable but also close the value-added loop demanded by a circular economy. Lucarini et al. (2021) reviewed the processing technologies involved in the recovery and refining of valuable chemical components from waste streams from the fruit industry, and Struck et al. (2016) discussed berry pomace processing to recover polyphenols and fibers.

Berry pomace has approximately 50–60% moisture, and it is usually air-dried to avoid microbial spoilage. The dry pomace contains 4–10% [dry basis (d.b.)] total phenolic compounds and 50–70% (d.b.) food fibers, most of the insoluble type (Struck et al. 2016). Natural antioxidants extracted from pomace could replace synthetic compounds added to foods to deter lipid oxidation that must be declared on labels and are suspected to cause negative health effects (Struck et al. 2016). Alternatively, the residue after juice extraction can be further fractionated and refined into a functional fiber-rich ingredient, vitamins, and other nutrients (Alba et al. 2019). Eco-friendly cold-pressed oils from berry seeds in the pomace are already commercially available to the food and nutraceutical industries (Cheikhyoussef et al. 2020). These berry oils are rich in essential fatty acids, with a favorable low ratio of ω-6 to ω-3 fatty acids, and include abundant antioxidants (Van Hoed et al. 2009). Spent solids from the alcoholic fermentation of berries subjected to eco-friendly extraction technologies may yield valuable phytochemicals or be used directly as a source of energy in industrial operations (Mauricio et al. 2020).

HEALTH BENEFITS OF BERRIES

Berries are regarded as important constituents of a healthy diet. Nutritionally speaking, berries are low in calories, lipids, and sodium and are good sources of dietary fibers (including, in some cases, soluble fibers), essential minerals, and vitamin C. In addition, berries are important sources of BACs and other antioxidants.

Antioxidants in Berries

Antioxidant molecules are present in all edible plant foods. Phenolic compounds (polyphenols) and ascorbic acid (vitamin C) are major antioxidants in berries, and several articles discuss their relative contents, chemical structures, reactivity, and bioactivity (Beattie et al. 2005, Olas 2018, Nile & Park 2014, Pap et al. 2021, Shahidi & Ambigaipalan 2015, Tian et al. 2017, Zorzi et al. 2020). This review alludes mostly to the presence of phenolic compounds and ascorbic acid as markers of antioxidant activity and contributors to the alleged health properties of berries and berry products. **Figure 2** depicts some of the major antioxidant compounds reported for berries and their susceptibility to temperature and other key processing variables (Barbosa-Cánovas et al. 2022, Nile & Park 2014).

Phenolic compounds are secondary metabolites consisting of one or more aromatic rings with variable degrees of hydroxylation, methoxylation, and glycosylation (Manganaris et al. 2014, Pap et al. 2021). They abound in several other plant-derived foods such as tea, red wine, coffee, and dark chocolate. The main phenolic compounds in berry fruits are phenolic acids, flavonoids, tannins, anthocyanins, lignans, and stilbenes (**Figure 2**). Their chemical formulae can be found in Beattie et al. (2005) and Pap et al. (2021).

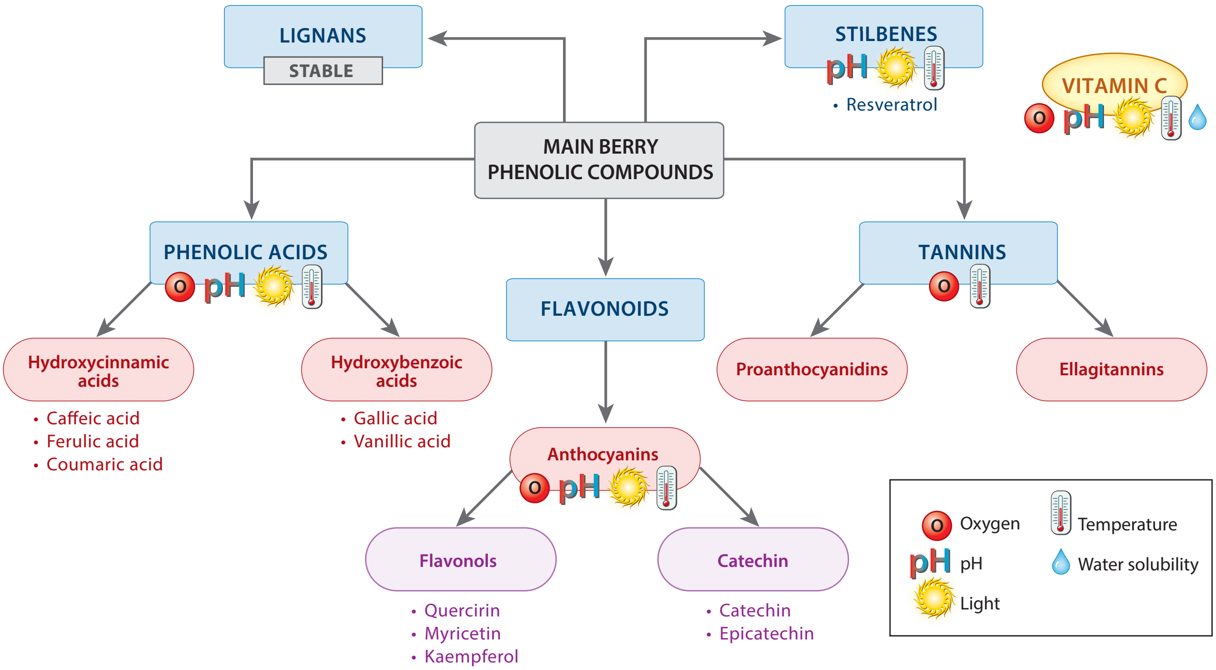

Figure 2

Major antioxidants and bioactive components in berries. Also shown are processing variables that affect their retention and bioactivity.

Determination of the Antioxidant Activity

The antioxidant activity of berries is determined in vitro as the chemical capacity of a berry extract to inactivate a free radical or convert it into a passive form. Common assays measure the transfer of a hydrogen atom [e.g., oxygen radical absorbance capacity (ORAC) and total peroxyl radical antioxidant parameter] or the transfer of electrons from antioxidants to free radicals [e.g., cupric reducing antioxidant capacity (CUPRAC) and ferric reducing antioxidant power (FRAP)], and mixed mechanisms [e.g., 2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) radical scavenging activity (ABTS) and 2,2-diphenyl-1-picrylhydrazyl radical scavenging activity (DPPH)] (Munteanu & Apetrei 2021). Often, a total antioxidant capacity (TAC) is reported to represent the overall antioxidant activity of the different compounds, including vitamin C (Munteanu & Apetrei 2021, Olas 2018). Most of these analytical methods are simple to implement, but the interlaboratory variability for the same assay is high and in most cases there is no correlation between the antioxidant activity determined by different assays of the same sample (Niki 2011).

Pellegrini et al. (2018) state that in many scientific articles a high in vitro antioxidant activity is associated with potential beneficial physiological effects, i.e., berries with higher values in any of the previous assays are healthier than those with lower values. This is scientifically unacceptable and creates confusion for consumers and researchers. The results of these analytical procedures are now considered as being biologically irrelevant (Munteanu & Apetrei 2021, Witkamp 2022). However, the determination of antioxidant activity may be a useful tool to monitor changes during processing and storage.

ORAC: oxygen radical absorbance capacity

CUPRAC: cupric reducing antioxidant capacity

FRAP: ferric reducing antioxidant power

ABTS: 2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) radical scavenging activity

DPPH: 2,2-diphenyl-1-picrylhydrazyl radical scavenging activity

TAC: total antioxidant capacity

Claimed Health Benefits of Berries

Regular consumption of berries has been associated with delayed mortality and a decreased risk of some cancers, stroke, coronary heart disease, and other pathologies (Hjartåker et al. 2014, Kalt et al. 2020). The principal hypothesis for the protective health effects of berries has been the presence of natural phenolic compounds and antioxidants. In particular, considerable attention has been given to the beneficial role in human health of phenolic compounds present in berries (Basu et al. 2014, Lavefve et al. 2020, Silva et al. 2020). Unrelated to their antioxidant effect, polyphenols may reduce the rate and extent of digestion of starch, protein, and lipids, thus decreasing hyperglycemia and aiding body weight control (Boath et al. 2012, Olas 2018). For comprehensive reviews on the beneficial health properties of berries and berry foods, the reader may consult Bonyadi et al. (2022), De Amicis et al. (2022), Golovinskaia & Wang (2021), and Vahapoglu et al. (2021).

Berries, popularized as super fruits, exhibit a high in vitro antioxidant activity that rates them at the top among commonly eaten foods (Kalt et al. 2020, Salo et al. 2021). Values of in vitro antioxidant analyses such as Trolox equivalent antioxidant capacity, DPPH, ORAC, CUPRAC, and FRAP are commonly used in health-food magazines and on Internet websites to support berries as superfoods, although some of them (e.g., ORAC) have no relevance to human health (Schaich et al. 2015). Moreover, no antioxidant compound by itself can arrest the deleterious oxidative damage of biological molecules mediated by multiple endogenous oxidants (Niki 2021). Thus, several studies conclude that there is no direct link between a high in vitro antioxidant capacity value and explicit health benefits (Finley et al. 2011, Kotha et al. 2022, Pellegrini et al. 2018). Moreover, multiple interactions (additive, synergistic, and antagonistic) are known to occur between combinations of diverse antioxidant compounds, either in purified form or in crude extracts (Chen et al. 2022, Zhang et al. 2019).

Interventional and randomized clinical studies are the gold standards to validate the health effects of foods, but results are slow to manifest and usually subtle (Witkamp 2021). Additionally, diet–disease studies have been criticized as being based on simple observational designs and substandard measurements (Brown et al. 2021). Despite these shortcomings and other sources of bias, claims of causality are commonly made regarding the health benefits of berries and berry products supported by human-based studies. **Table 1** summarizes information selected from studies and major reviews available in the past decade, suggesting that most clinical and trial interventions are cautious in their conclusions and recommendations. Other results on controlled trials of berry-based food interventions in humans are presented by Basu et al. (2014), Bonyadi et al. (2022), and Lavefve et al. (2020). Data in **Table 1** reveal the general difficulty in drawing cause–effect conclusions from clinical studies involving berries and berry products because of the many confounding factors (Munialo et al. 2019). Furthermore, the inconsistency of studies investigating the effects of pure berry BACs and antioxidants on human health reinforces the importance of the synergistic interactions between the mixture of phytochemicals and other nutrients in whole berries (Basu et al. 2014, Nayak et al. 2015, Zhang et al. 2019).

Evidence starts to amount to the role of BACs in berries in the modulation of the gut microbiota and the positive health implications of the resulting metabolites (Lavefve et al. 2020, Pap et al. 2021, Witkamp 2022). Improvements in gut health, lowering elevated LDL cholesterol, and decreasing the risk of CVDs, several cancers, stroke, and type 2 diabetes have been attributed to the dietary fiber content in berry fruits (Dreher 2018). Interactions between dietary fibers and polyphenols mediated by the gut microflora yield bioactive phenolic catabolites that may inhibit inflammatory processes and reduce obesity and have a profound effect on human health through the gut–brain axis (Rodriguez-Daza et al. 2020, Thomson et al. 2021).

In summary, a plausible explanation for the observed long-term health benefits of the consumption of whole berries is a combined effect of the presence of phytochemical components (and their metabolites), micronutrients, high content of fibers, and the synergistic interactions with other nutrients and metabolites during digestion and colonic fermentation (Lavefve et al. 2020, Foito et al. 2018). Future research should gather reliable data and supportive evidence from rigorous long-term clinical studies to provide an understanding of the underlying mechanisms leading to the beneficial effects of berries (Foito et al. 2018, Olas 2018, Pap et al. 2021, Witkamp 2022). The application of artificial intelligence and machine learning algorithms, as well as the use of ‘omics technologies, may assist in bridging the gap between the data emanating from in vitro and in vivo assays and specific health effects assessed by nutritional epidemiology (Côté & Lamarche 2022, Karlund et al. 2014, Wang et al. 2022, Witkamp 2022).

EFFECT OF PROCESSING VARIABLES ON BIOACTIVE COMPONENTS

Studying the effects of processing on BACs of berries is complicated because of the large chemical variability of the raw materials, ways of reporting processing conditions, and the intrinsic inconsistency of the analytical procedures. Several articles review the effect of processing variables on the quality and content of BACs in berries and similar small fruits (Debelo et al. 2020, Karlund et al. 2014, Li et al. 2017). This section focuses primarily on the effects of postharvest storage and processing of berries on the antioxidant capacity of phenolic compounds and vitamin C.

Most phenolic compounds in fruits are severely damaged in their stability and bioavailability by thermal treatments and high pH conditions, particularly after being released from the cellular matrix (Arfaoui 2021). In fruit processing, vitamin C degrades into dehydroascorbic acid in the presence of oxygen, and it is poorly retained during high temperature–long time conditions and by leaching into an aqueous medium (Giannakourou & Taoukis 2021). **Figure 2** shows the susceptibility of BACs in berries to degradation by major processing variables. **Table 2** presents data on specific processing effects on the antioxidant capacity of different berries.

Table 1 Selected information on human intervention studies of berries and berry products (past 10 years)

Berry source	Type of study/report	Main conclusions	Reference
Strawberry	Epidemiological and clinical studies. Mostly controlled trials fewer than 12 weeks in duration	Strawberries exhibit antioxidant, anti-inflammatory, and antihypertensive properties. Potential of reversing neurodegenerative disorders needs further investigation	Basu et al. 2014
Several berry species	Review of clinical research on the potential health benefits of berries and berry products	A berry-rich diet may improve plasma lipid profile, reduce chronic inflammation, and support cardiovascular health	Yang & Kortesniemi 2015
Strawberry and strawberry products	Review of promising health benefits of consumption of strawberries, with a special focus on human studies	BACs seem to be responsible for therapeutic effects. Further clinical trials are needed to demonstrate prevention of cancer and age-related neurodegenerative disorders	Afrin et al. 2016
Several berry species	Analysis of the effects of consuming berries (or their phytochemicals) on several neurodegenerative and noncommunicable diseases	Epidemiological and intervention studies do not fully support the premise that polyphenol-rich diets have health benefits relevant to some disease conditions	Foito et al. 2018
Blueberry	Six-month trial on the effect of blueberry intake on insulin resistance and metabolic syndrome	150 g of blueberries/day resulted in sustained improvements in cardiovascular function and lipid status (e.g., higher HDL cholesterol), but insulin resistance remained unchanged	Curtis et al. 2019
Blueberry	Selected research based on human observational and clinical evidence	Evidence differs in supporting cardiovascular, gluco-regulation, neuroprotection, and vision benefits. The dose dependency of clinical effects is mostly unclear	Kalt et al. 2020
Blueberry and blueberry-based products	Review with particular relevance given to available in vivo and epidemiological studies	Some evidence supports a beneficial role of consumption of berry extracts; however, further human-based studies are recommended	Silva et al. 2020
Berries in general	Review of the consumption of berries as potential medicinal foods based on pharmacologically active compounds	BACs exert protective effects against inflammatory and metabolic disorders, CVDs, and several cancers. Further clinical trials are required to provide adequate evidence	Golovinskaia & Wang 2021
Several berry species	Survey of the effect of berry consumption on the cognitive functions in healthy subjects	Unable to find consistent effects across studies and methodologies. For the majority of outcomes, no significant effects were apparent	De Amicis et al. 2022
Berries and berry products	Review of short-term clinical trials on the effects of berry products on cognitive performance in the elderly	Fresh berries and berry supplements are endorsed as part of a healthy diet. Further research should assess the significance of results in longer times	Bonyadi et al. 2022

Abbreviations: BACs, bioactive compounds; CVDs, cardiovascular diseases; HDL, high-density lipoprotein.

Table 2 Effect of storage/processing on bioactive compounds in berries and berry products

Process	Berry type	Effect on bioactive compounds	References
Postharvest storage	Strawberry and other berries	TPCs and total flavonoids in red ripe strawberries were better retained when stored at 3°C/65% RH than at 10°C/95% RH	Karlund et al. 2014
		Fast precooling to 1°C and postharvest storage at low temperatures under modified and controlled atmospheres reduced microbial growth and delayed senescence but decreased TPCs and AC	Horvitz 2017
		Strawberries stored at 5°C showed higher TAC, TPCs, and AC compared to those stored at 1°C but had a 30% shorter postharvest life	Ayala-Zavala et al. 2004
Dehydration	Several berry species	Antioxidant activity (ABTS) of blueberries was significantly reduced to almost half after 6 h of air-drying at 80°C	Reque et al. 2016
		ORAC values were 20–40% lower in air-dried strawberries and blueberries than in freeze-dried ones. Vitamin C content was drastically reduced (50–70%) by air-drying	Nemzer et al. 2018
		Air-drying (65°C) of raspberries and blueberries caused a significant reduction in anthocyanins, TPCs, and antioxidant activity (ABTS), whereas freeze-drying increased the content of antioxidants	Sablani et al. 2011
		Extracts of three berry species were spray-dried with 20% maltodextrin (air temperature, 170°C). Loss of AC was less than 8%, and TPC and ABTS values of powders increased	Gagneten et al. 2019
		Cranberry juice spray-dried (185°C) with different encapsulating biopolymers showed increased TPCs, AC, and ABTS values compared to the control. No changes in BACs occurred in powders stored for 12 weeks at 25°C	Zhang et al. 2020
Freezing	Several berry species	IQF blueberries exhibited almost no change in TPCs, vitamin C, and antioxidant activity (FRAP) after freezing. Loss of anthocyanins was 12% after 10 months of storage at −18°C	Poiana et al. 2010
		IQF berries had higher retention of ascorbic acid, TPCs, and AC than did slow-frozen samples, although a decrease in ascorbic acid occurred in both cases	Žlabur et al. 2021
		IQF berries showed no changes in antioxidant capacity or AC after long-term storage at −20°C	Hager et al. 2008
		Irrespective of freezing method, strawberries retained bioactive compounds and had enhanced content of bioaccessible anthocyanins	Kamiloglu 2019
Jam production	Bilberry	Jams cooked under vacuum (68–70°C) showed 17–30% higher antioxidant activity than those heated in an open kettle	Korus et al. 2015
	Raspberry	No change in total phenolics by heating (104–105°C) during jam processing	Nayak et al. 2015
	Strawberry	Jams stored at 4°C kept their red color and had a higher content of anthocyanins and total antioxidant capacity (FRAP value) than samples stored at 20°C	Wicklund et al. 2005

(*Continued*)

Table 2 ***(Continued)***

Process	Berry type	Effect on bioactive compounds	References
Juice production	Several berry species	Pasteurized blackberry, blueberry, cranberry, raspberry, and strawberry juices suffered a greater loss of TPCs (4–97%), AC (8–292%), and vitamin C (up to 39%) compared to pressed juice	Leong & Oey 2017
	Blackberry	Juices pasteurized at 75.8°C/15s and 92.8°C/10s exhibited lower DPPH scavenging capacity (<26%) and AC (<9%) than the control, with no changes in ORAC values. However, protection against lipid peroxidation remained unchanged in ex vivo models	Azofeifa et al. 2015
	Strawberry	HPP-treated strawberry juice had higher TPCs, vitamin C, AC, FRAP, and TEAC values than a thermally pasteurized juice (85°C)	Predná et al. 2016
Puree manufacture	Blueberry	Blanching (3 min, 95°C) followed by pasteurization reduced the total monomeric anthocyanins by 43% compared to a fresh puree	Nayak et al. 2015
	Honeysuckle berry	Ascorbic acid content in purees from several cultivars was reduced by 33%–57% after 2 months of storage at 20°C and no light	Grobelna et al. 2019
Fermentation	Strawberry	AC decreased by 19% after alcoholic fermentation of juice to wine and 91% during acetic fermentation to vinegar, inducing color changes from red to orange	Hornedo-Ortega et al. 2017
	Blueberry, blackberry	Fermentation of juices with probiotic bacteria enhanced the ABTS radical scavenging activity by 40–60% and improved sensory quality	Wu et al. 2021

Abbreviations: ABTS, 2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) radical scavenging activity; AC, antioxidant content; BACs, bioactive compounds; DPPH, 2,2-diphenyl-1-picrylhydrazyl radical scavenging activity; FRAP, ferric reducing antioxidant power; HPP, high-pressure processing; IQF, individually quick freezing; ORAC, oxygen radical absorbance capacity; RH, relative humidity; TAC, total antioxidant capacity; TEAC, Trolox equivalent antioxidant capacity; TPCs, total polyphenolic compounds.

State of the Fruit Matrix

Nutrients and BACs in fruits are well described in terms of their composition profiles and chemical characteristics. However, their specific location in the fruit matrix and chemical interactions at multiple dimensional scales (e.g., molecular, subcellular, and cellular) are largely unknown (Fardet 2017). Free, bound, and conjugated polyphenols in fruits accumulate in the cell wall, the vacuole, and possibly the cell nuclei, whereas ascorbic acid is mostly located in chloroplasts and the vacuole (Hutzler et al. 1998, Nayak et al. 2015). Degradation and obliteration of cell walls and cellular membranes caused by enzymes, bruising, and/or processing, release BACs from the cellular matrix, making them more prone to oxidation, enzymatic degradation, and other chemical reactions. Thus, the physical state of the food matrix before and during processing influences the profile and bioactivity of phytochemicals in finished products (Arfaoui 2021, Ifie & Marshall 2018, Shahidi & Pan 2021).

Storage of Fresh Fruits

Postharvest storage aims at prolonging edible quality by arresting the natural senescence process and microbiological decay. Most berries are nonclimacteric fruits, so when harvested at or near full maturity they continue to respire. Berries ripen quickly and nonuniformly, so they are harvested daily or every 2–3 days by selecting fruit in the right ripening stage and avoiding damage to the fruit during picking and handling. A prompt and fast precooling after picking is essential to remove the field heat and slow down the physiological and biochemical activities leading to changes in BAC content and quality during storage (Duan et al. 2020). After sorting, grading, and packing, berries are usually stored at low temperature (e.g., 1–5°C), at high relative humidity (e.g., 70–90%), and under controlled or modified atmosphere conditions with high CO_2 and low O_2 concentrations (Di Vittori et al. 2018, Karlund et al. 2014).

Although ascorbic acid content usually declines during storage, the concentration of some phenolic compounds may even increase due to endogenous metabolism (Beattie et al. 2005). High CO_2 storage generally decreases TPCs, AC, and TAC (Manganaris et al. 2014). An extensive review of postharvest effects on raspberries concluded that storage at 1–2°C increased the anthocyanin content and ascorbic acid content remained unchanged, whereas the concentration of phenolic compounds showed mixed results (Lo Piccolo et al. 2020). The large number of intrinsic and extrinsic factors intervening during postharvest often leads to contradictory data for changes in the content of TPCs, anthocyanins, and ascorbic acid of different berry species (Horvitz 2017, Karlund et al. 2014, Lo Piccolo et al. 2020).

Freezing and Low-Temperature Storage

Several berry species subjected to conventional freezing or IQF exhibit minor or no changes in the concentration of phenols, ascorbic acid, and in vitro antioxidant activity (Neri et al. 2020). During long-term cold storage, IQF fruits experienced a lower reduction in BACs than did slowly frozen berries (Poiana et al. 2010, Žlabur et al. 2021). Long-term frozen storage at lower temperatures (e.g., −40°C versus −18°C) favored the retention of BACs (Stevanović et al. 2021). As pointed out by Neri et al. (2020), analysis of data for the effect of freezing of fruits is difficult to interpret because of poor characterization of the raw materials (e.g., cultivar and stage of maturity), ambiguously reported processing and storage conditions, and the different methods used to express antioxidant activity (e.g., DPPH, ABTS, or FRAP).

Removal of Water (Dehydration)

Water removal is a convenient method to preserve, store, transport, and commercialize berries at ambient temperature. High temperatures and long processing times as often encountered in air-drying are detrimental to BACs in berries. Thus, berries air-dried at 65°C for 20 h showed higher TPC content and radical scavenging activity than any other temperature–time combinations (Arfaoui 2021). A significant reduction in anthocyanins, phenolics, and antioxidant activity was reported for air-dried berries compared to freeze-dried samples (Sablani et al. 2011, Li et al. 2021). Freeze-drying is considered the best dehydration method for preserving the fruit matrix structure and maintaining a high content of BACs (Lo Piccolo et al. 2020).

For a selected group of berry juices and extracts, freeze-drying and spray-drying are the recommended dehydration technologies to preserve BACs (Ravichandran & Krishnaswamy 2021). Spray-drying is widely utilized to produce berry powders and encapsulate polyphenolic compounds in various types of matrices (Robert & Fredes 2015). Short exposure to high temperatures and the fast formation of a dry encapsulating matrix yield a high recovery of phenolic compounds and enhanced protection during storage (Zhang et al. 2020).

Mechanical Processing

The manufacture of several berry products requires the crushing of the fruit (**Figure 1**). Disruption of the cellular matrix to make juices, jams, or wine breaks open the fruit cells and exposes their chemical contents to oxidation, endogenous enzymatic transformations, and other chemical interactions (de Oliveira et al. 2021, Horvitz 2017, Karlund et al. 2014). In particular, interactions of polyphenols extracted during processing with remnants of cell walls and cell wall components (e.g., pectin and hemicelluloses) may result in the formation of complexes that modify the bioavailability and bioactivity of phenolic compounds (Siemińska-Kuczer et al. 2022).

HPP: high-pressure processing

High Temperature

Direct thermal processing is utilized in blanching, jam production, and pasteurization/sterilization of juices and purees (**Figure 1**). Temperature–time combinations used in thermal processing may cause the degradation of heat-sensitive antioxidant compounds, influence enzyme activity, and alter the bioavailability of BACs. Exposure to high temperatures (e.g., as in pasteurization and sterilization) reduced the content of most polyphenolic compounds and vitamin C, although the mechanisms are probably specific for different food matrices (Gao et al. 2022, Giannakourou & Taoukis 2021). Losses in ascorbic acid (33–57%) and flavonols (6–50%) were reported during jam-making and subsequent storage (Grobelna et al. 2019). Large losses in anthocyanins and vitamin C occurred during the manufacture of berry juices and berry purees (Beattie et al. 2005, Patras et al. 2009). High temperatures (e.g., >90°C) during drying of pomace resulted in considerable losses of several BACs (Struck et al. 2016).

Inconsistent results often observed during thermal processing of fruits (e.g., blanching, pasteurization, and cooking) may be due to a combination of factors, including the time–temperature combinations at which heat-sensitive phytochemicals and vitamin C are exposed during processing, the degree of release of BACs from the cellular matrix and inactivation of degrading enzymes, the presence of oxygen, and the formation of new compounds with potential antioxidant capacity (Nayak et al. 2015, Verghese et al. 2021).

High Pressure

Strawberry and blueberry juices subjected to high-pressure processing (HPP) showed either no change or a slight reduction in TAC depending on the pressure level, type of juice matrix, and method of antioxidant assay used (ORAC or FRAP) (Tadapaneni et al. 2014). HPP of strawberry and blackberry purees retained important BACs (e.g., ascorbic acid and anthocyanins) and preserved the color intensity better than conventional thermal treatments (Patras et al. 2009). An increase in the content of BACs is usually associated with a higher extractability caused by pressurization that damages the cell walls, whereas a decrease may be explained by the activation of some degrading enzymes.

Data in **Table 3** are difficult to interpret, and the understanding of the concurrent mechanisms leading to the gain or losses of bioactives is limited (Debelo et al. 2020, Karlund et al. 2014). Comparison of results should be made with caution given the different specificity of analytical methods and the effect of variables usually not controlled during processing such as pH and water activity.

Several reasons may explain some of the inconsistencies in results regarding the effect of processing on BACs. First, there are intrinsic chemical differences between and within species of berries and the physiological state of the fruit during experimentation. Second, the physical state of the fruit matrix influences the extraction of BACs and exposure to biochemical reactions and chemical interactions. Third, there is a confounding effect of processing conditions (e.g., treatment duration, level of processing variables, and pH). Third, different analytical methodologies are used to assess the antioxidant capacity and ways of reporting the data (i.e., wet or dry basis of whole fruit or extracts).

Table 3 Novel technologies for berry processing

Process technology	Application	Advantages/disadvantages	Reference(s)
High-pressure homogenization	Juice extraction	Improved extraction of antioxidant components but reduced color stability of blackcurrant juice	Kruszewski et al. 2021
High-pressure processing	Long-term storage of fresh fruits	Higher antioxidant activity compared to thermal blanching but reduced texture relative to fresh blueberries	Paciulli et al. 2019
Irradiation	Prolonged storage of fresh fruits	Gamma-irradiated strawberries and blueberries exhibited reduced fungal decay during refrigerated storage but lower sensory attributes than untreated berries	Panou et al. 2020, Wang & Meng 2016
Enzymatic	Juice and pomace extraction	Enzyme-aided juice pressing enhanced blackcurrant juice yield, decreased the AC in juice, and increased polyphenols in press-residue	Rätsep et al. 2020
Ultrasound	Extraction of bioactive compounds	Faster extraction rate of anthocyanins and phenolic compounds from myrtle berries	González de Peredo et al. 2019
Enzymatic/ ultrasound	Juice extraction from mash	Slight increase of juice yield for black, red, and white currants; improvement in TPC content, antioxidant capacity, and vitamin C recovery	Kidon & Narasimhan 2022
Thermosonication	Pasteurization	Improved bioavailability of anthocyanins, total flavonoids, and quality properties of camu camu nectars	Do Amaral Souza et al. 2019
PL	Juice pasteurization	PL-treated gooseberry juice retained color, antioxidant activity, and vitamin C better than pasteurized control; PL was slightly effective in decontaminating fresh strawberries from inoculated *Salmonella*	Chakraborty et al. 2020, Cao et al. 2019
PEFs	Fresh product quality	PEFs and a sanitizing solution significantly reduced the microbial load and increased anthocyanins and phenolic compounds in fresh blueberries but softened the texture	Jin et al. 2017
	Pretreatment before juice extraction	PEFs significantly increased the yield, TPCs, and antioxidant activity of blueberry juice	Lucarini et al. 2021
Microwaves	Blanching	Microwaved-blanched strawberries presented a better texture and fewer color changes than steam-blanched fruits	Matsui et al. 2018
V/MW	Dehydration	V/MW drying improved the residual moisture content, rehydration ratio, texture, and color of dried berries	Calín-Sánchez et al. 2020, Meda et al. 2016
CAPP	Microbial decontamination	Bacterial growth (but not fungal growth) was effectively reduced during storage of CAPP-treated blueberries without affecting color, ascorbic acid, or AC	Pathak et al. 2020
Microfiltration	Juice clarification	Ceramic membranes produced chokeberry juices with a relatively high BAC content and low turbidity and viscosity after pasteurization	Lachowicz et al. 2019
Ozone	Long-term storage of fresh fruits	Gaseous ozone increased marketable volume of several berries while maintaining firmness	Huynh et al. 2019

(*Continued*)

Table 3 (*Continued*)

Process technology	Application	Advantages/disadvantages	Reference(s)
SFE	Valorization of berry seeds	Oils extracted from berry seeds with supercritical fluids contained high contents of PUFAs, antioxidant compounds, and vitamin E and exhibited good antioxidant activity	Gustinelli et al. 2018
Edible coatings	Shelf-life extension	Edible coatings and probiotics protected berries against postharvest diseases and preserved fruit quality	Romero et al. 2022
Nanotechnologies	Nutraceuticals and delivery systems	Nanodelivery systems protected berry polyphenols from degradation in the gut and enhanced their bioavailability	Forbes-Hernandez 2020

Abbreviations: AC, antioxidant content; BAC, bioactive compound; CAPP, cold atmospheric pressure plasma; PEFs, pulsed electric fields; PL, pulsed light; PUFAs, polyunsaturated fatty acids; SFE, supercritical fluid extraction; TPCs, total polyphenolic compounds; V/MW, vacuum/microwaves.

ADVANCES IN BERRY PROCESSING TECHNOLOGIES

Novel postharvest and processing technologies aim at providing, in a sustainable way, fresh berries and berry products with safe and superior edible quality, high nutritive value, and extended shelf life (Huynh et al. 2019, Khan et al. 2018, Li et al. 2017). There has been a growing interest in the application of nonthermal processing technologies (NTPTs) that minimally modify the sensory and nutritional properties of fresh fruits and their products (Barbosa-Cánovas et al. 2022, Jadhav et al. 2021). Among these technologies are HPP, irradiation, pulsed electric fields (PEFs), oscillation magnetic fields, ultrasound, cold atmospheric pressure plasma, and membrane processing (Boateng 2022, Bevilacqua et al. 2018, Jadhav et al. 2021, Varalakshmi 2021). Suggested principles of action and major effects of these technologies on BACs, antioxidants, and the microstructure of fruits are presented by Barbosa-Cánovas et al. (2022) and Boateng (2022).

High-pressure technologies are already well-established in the pasteurization of several fruit products. Rosenthal et al. (2018) reported that antioxidant activity varied widely during the storage of pressurized berry products, but the trend decreased in time (faster at increasing storage temperatures). HPP and high-pressure homogenization had no major effects on the AC and antioxidant activity of berry juices and pulps, and, in a few cases, the values even increased because of the extraction of hydrolyzable tannins present in the fruit skin (Pérez-Lamela et al. 2021).

Several membrane technologies (e.g., microfiltration, reverse osmosis, and ultrafiltration) are already used in the berry juice processing industry for clarification, fractionation, and concentration, resulting in low thermal damage, increased aroma retention, and reduced energy consumption. These pressure-driven membrane technologies are being replaced by other membrane operations such as osmotic membrane distillation and pervaporation that better preserve natural aromas and AC (Conidi et al. 2020).

Among emerging dehydration technologies, those based on combined methods like vacuum/microwave drying and osmotic dehydration pretreatments remove moisture at low temperatures and are less harsh on most phytochemicals than conventional air-drying (Calín-Sánchez et al. 2020).

Novel technologies for the recovery of BACs from residues of berry processing may be divided into preprocesses that facilitate their extraction from the fruit matrix, such as ultrasound, PEFs, and microwaves, and extraction procedures that isolate specific compounds. Supercritical fluid extraction and pressurized liquid extraction (e.g., using water–ethanol mixtures) are promising green technologies with high selectivity for lipids (e.g., oils in seeds) and polar compounds, respectively (Piasecka et al. 2022).

NTPTs: nonthermal processing technologies

PEFs: pulsed electric fields

As recently reviewed by Ahmed et al. (2020), some NTPTs are more effective than others in inactivating viruses in fresh berries. Viruses in voids and cavities between the drupelets may not be exposed to the treatment (e.g., pulsed light and UV), thus reducing their effectiveness. Irradiation doses for efficient virus inactivation exceed the current legal limits and cause important deterioration in the sensory quality of berries. High pressures in combination with other NTPTs seem to be an effective method to inactivate viruses while minimizing undesirable changes in the texture and color (Paciulli et al. 2019).

Table 3 exemplifies some applications of novel technologies in the processing and preservation of berries and berry products. As asserted by Barbosa-Cánovas et al. (2022), results from different studies on the effects of NTPTs are difficult to compare and interpret because of the disparity of treatment conditions and analytical methodologies. However, the general trend is that NTPTs minimize the impact of processing on quality attributes and the content of BACs. Despite considerable research efforts in the application of novel technologies, conventional processing (e.g., thermal treatments) is still dominant in the berry industry (Li et al. 2017). Pressures to implement eco-friendly technologies and a circular economy together with consumers' demands for clean product labeling and minimally processed foods are likely to promote the adoption of several processing technologies discussed in this section.

Mention has to be made of the remarkable advances in recent years in the application of novel genomic technologies for improved berry breeding. Among them are the identification of the genetic basis controlling the accumulation composition of health-promoting components, the identification of biomarkers for important commercial and nutritional traits, and the application of metabolomics to evaluate the contribution of environmental and genetic factors on the composition of BACs and metabolites (Mengist et al. 2022, Senger et al. 2022).

CONCLUSIONS

Berries and berry products are recommended as part of a healthy diet and are a flavorful, diversified food intake. The production of berries has doubled in the past decade, and year-round consumption of fresh fruit is possible because of counter-seasonal imports. In addition, several processing technologies provide a myriad of shelf-stable products. Most of the invoked health benefits of berries are attributed to the high content of phenolic compounds and antioxidants with potential effects on preventing or alleviating some chronic NCDs. Technologies that prolong the shelf life of fresh berries or stabilize berries as food products affect the content and activity of these compounds in diverse ways. Effects of processing are difficult to interpret because of the intrinsic variability of the raw materials, the multiplicity of intervening processing variables, and the ambiguity of the data reported. A substantial variation in the concentration of antioxidant compounds in fresh berries is due to genetics, environmental factors, and postharvest manipulation. During processing, several phenomena take place simultaneously, including the release of BACs and nutrients from the cellular matrix, the inactivation of degrading enzymes, the formation of new compounds with potential antioxidant capacity, and the loss of heat-sensitive phytochemicals and vitamin C under various time–temperature combinations. Several in vitro analytical methods are used to report antioxidant activity and vary in their extraction procedures and the underlying chemical reactions complicating their interpretation and relevance. Further studies are needed to take into consideration these shortcomings in planning experiments, interpreting results, and drawing conclusions on the effects of processing and in the development of milder technologies and novel products.

Regarding health aspects, there is a consensus that a high in vitro antioxidant content does not translate per se into more effective actions at the biological level. Clinical and longitudinal studies are not conclusive on the effects of berries or single components in preventing or alleviating some NCDs. Focusing on only these potential effects distracts consumers from the otherwise recognized health benefits of berries as fruits. Research efforts should concentrate on the components of the whole berry matrix and their release, interactions, and metabolites as part of a mixed dietary intake, rather than on the effects of single compounds. As suggested above, a plausible explanation for the unique health benefits of berries is a multifactorial effect of complex mixtures of abundant phenolic components, antioxidants, and their metabolites acting synergistically or additively with other nutrients like fiber and micronutrients. Evidence of the interplay between several berry components, the gut microbiota, and the brain is accumulating. Artificial intelligence and machine learning algorithms may assist in the analysis of the complex data emerging from future studies. Further research should focus on understanding the mechanisms involved in the health-promoting roles of berry components.

DISCLOSURE STATEMENT

The author is not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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