Use of Berry Pomace to Design Functional Foods

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REVIEW

Use of Berry Pomace to Design Functional Foods

Elena Diez-Sánchez, Amparo Quiles, and Isabel Hernando

Department of Food Technology, Universitat Politècnica de València, Valencia, Spain

ABSTRACT
The demand for healthy products has led researchers and industry to develop sustainable foods with high nutritional properties. Berry pomace is a by-product from the juice industry, and a valuable source of bioactive compounds. Its composition allows it to be used as a functional ingredient with antioxidant and antimicrobial properties. Moreover, pomace possesses specific techno-functional properties that can lead to changes in the characteristics of the food where it is incorporated. The objective of this work is to collect current knowledge of composition, nutritional, and techno-functional properties of berry pomace, and its use as an ingredient in different foods.

KEYWORDS
By-product; valorization; polyphenols; dietary fiber

Introduction

To date, there is a growing market for natural foods where, beyond the nutritional benefit, a health benefit is obtained. This growth is driven by a growing demand for healthy food from an increasingly health-conscious consumer base. These food products are known as "functional foods," which are defined as:

> "*the food comprising at least one ingredient which when consumed brings a beneficial effect exceeding the normal and adequate nutritional effect, whereas this ingredient (or these ingredients) may be naturally present in food, or food may be fortified (enriched) with it*".[1]

Therefore, the food and beverage industries' technology has progressed and explored alternative sources of bioactive ingredients because of its great interest and importance.[2,3]

Generation of food waste is a great concern in the social, economic, and environmental points of view. Main surplus in fruit and vegetable processing are by-products and production line waste, thus, the current linear food supply chains need to change towards more sustainable food supply chains based on circular economy in which the by-products are recycled to re-enter the food supply chain.[4] The by-products are attracting special attention as functional, novel, and inexpensive ingredients, [5] because these by-products contain health-promoting phytochemicals and fibers. It is not a matter of trying to avoid waste generation, but to avoid the loss of the added value these by-products provide as health-promoting phytochemicals and fibers.[6] Thus, to change the concept of the by-product as a waste or something disposable (discarded material) toward something usable such as feedstock or raw material in food production, providing an added value is key.[7,8]

The by-products of berry juice processing are promising sources of dietary fiber and may be useful as a value-added ingredient with enhanced benefit for the formulation of functional foods and nutraceuticals.[9–11] Especially berry pomace, which comprises skin, pulp, and seeds, still have high amounts of valuable compounds. The seeds contain oil rich in polyunsaturated fatty acids and other pomace parts are rich in phenolic compounds and dietary fibers, which hold the characteristics required to be considered as functional ingredients due to their effects on human health.[12] Polyphenols can vary in their chemical structure and properties, from simple molecules, such as

CONTACT Isabel Hernando mihernan@tal.upv.es Department of Food Technology, Universitat Politècnica de València, Camino de Vera, s/n, Valencia 46022, Spain

phenolic acids, to highly polymerized molecules, such as proanthocyanidins. Its characteristic structure confers them its antioxidant capacity, which is the property related to health benefits.[13] Further, the effects of polyphenols in the prevention of certain diseases such as cancer [14,15] or type 2 diabetes, [16] and the alleviation of symptoms from gut inflammation [14] have been studied.

Notably, despite the high content of polyphenols in pomace, they are usually trapped or associated with fiber, which can affect their bioavailability and bioaccessibility. Therefore, their antioxidant capacity effect will be also affected.[12] During the *in vitro* digestion, the polyphenols may be released, and can undergo changes throughout the gastrointestinal tract due to the different conditions that occur along it.[17] For example, at low pH (gastric phase) anthocyanins, one of the most found phenolic compounds in berries, are in their most stable form, whereas at higher pH (intestinal phase) they can undergo modifications that make their absorption difficult.[18,19] Moreover, these polyphenols can interact with the different macronutrients in food, causing changes in the absorption of both phenolic compounds and some of the major components such as protein, fat, and carbohydrates.[20] The primary mechanisms involved are the formation of complexes or the inhibition of certain digestive enzymes, such as α-glucosidase and α-amylase.[21,22]

Giving an added value to these fruit residues by finding applications like food additives and valuable ingredients for functional food is important.[23] It is also a promising trend for achieving a substantial reduction in waste generation, one of the targets of the sustainable development goals set by FAO for the 2030 agenda.24[] Thus, in accordance with these consumer trends, using by-products generated from food industries could be a great opportunity to design healthy and natural food.

Thus, this review summarizes the current information available about berry pomace composition, nutritional value, and techno-functional properties. It is also focused on applying the different berry pomaces as an ingredient in food products.

Why choose berry pomace?

The food waste generated in EU is approximately 129 Mt, being the vegetables, fruits and cereals, the food groups producing the largest amount of food waste. Most food waste is generated at the consumption stage (46%), followed by the primary production (25%), processing and manufacturing (24%), and distribution and retail (5%) stages.[25] Thus, to avoid food waste, new alternatives for valorisation strategies need to be studied.

The pressing of berries in the fruit juice industry generates two materials: juice and pomace, being the yield of pomace obtained from pilot scale juice processing approximately 14%.[26] Berry pomace comprises peel, stems, and seeds. As described before, the pomace has an added value and thus, it should be considered as an alternative ingredient for the formulation of functional foods. However, one must remember that the pomace is a high-moisture product susceptible to microbial growth if storage conditions are not well controlled, thus, before being introduced into a formulation it must be processed.[7,27]

Berry pomace processing: drying

The pomace has a moisture content of approximately 60%, thus it is highly prone to microbial spoilage.[28,29] Hence, to facilitate its storage and stability, the pomace is subjected to moisture content reducing methods; for this, drying can be a good option to maintain its quality.

The drying process minimizes chemical and biological reactions during storage due to water removal.[7] However, drying processes affect the structure of the products giving place to powders with different solubility, bulk density, porosity, and color.[30] Moreover, drying can produce degradation of bioactive compounds, such as polyphenols; there is a greater degradation with the increase in the processing temperature.[31,32] Thus, it is important to choose the right drying process to obtain the best quality in the final products.

Hot-air convective drying is one of the most common method used for pomace powder obtention, but the main disadvantages are related to the degradation of phenolic compounds, such as anthocyanins, and the reduction of antioxidant capacity due to high processing temperatures.[31–33] To overcome this problem, other types of drying have been developed. An example is the microwave-assisted drying, this does not involve high temperatures and long times and could retain bioactive compounds present in non-processed pomace, but it has high installation and operating costs.[32] However, good results are not always obtained with using microwave-assisted drying; Oliveira et al. [34] found there were slight differences in phenolic compounds between hot-air drying and microwave-assisted drying. To optimize costs, both techniques could be combined; Zielinska et al. [32] found that hot-air drying at 60°C combined with microwave-assisted drying allowed shortening the time of hot-air drying and thus avoiding the chemical changes that occur with longer treatment times, and to lower the cost when using microwave-assisted drying alone.

Kerbstadt et al. [35] reported on different novel drying techniques such as infrared drying, infrared impingement drying, and microwave-assisted hot-air drying and compared them to freeze drying in bilberry press cake. They found that novel drying techniques could better preserve the anthocyanin content in comparison with freeze drying. In another study, Grimm et al. [36] compared continuous cyclone drying with the conventional batch fixed-bed convective drying on press cakes from different berries (bilberry, blackcurrant, and cloudberry). The results showed that if both drying processes are conducted at the same temperature, total phenolic contents are very similar regardless of the technique used. Thus, as cyclone drying consumes less energy, it could be a method for quick removal of free water before other drying processes.

There are different drying methods and process conditions, and the choice of their use will depend on various aspects such as cost, time, or phenolic degradation. However, it can be assured that temperatures above 60ºC, regardless of the drying method, negatively affect the phenolic content of the pomace.

Composition and nutritional properties of berry pomace

Besides the phenolic compounds, the pomace is composed of other compounds of great nutritional value. Table 1 summarizes the proximate composition of several berry pomaces. Notably, each fraction comprising the pomace is rich in different compounds. For example, regarding the lipid composition, the oil obtained from seeds is rich in γ-linolenic acid and stearic acid, whereas the seedless pomace is composed by policosanols and phytosterols.[54] Yao et al. [55] found that raspberry pomace without seeds and the raspberry seeds not only differed in lipid composition but also contained different amount of free, soluble-bound and insoluble-bound phenolics; and the raspberry pomace free phenolics had higher antioxidant capacity. Seeds can be a valuable material for fat extract obtention, whereas the seedless fractions are rich in dietary fiber and phenolic compounds.

The dietary fiber present in pomaces is usually higher than 20% (Table 1). This compound has important functional properties, which will depend on plant source, isolation method, degree of processing, insoluble dietary fiber to soluble dietary fiber (IDF/SDF) ratio, and particle size. From a nutritional viewpoint, the sources of DF used for fortification of foods should have a ratio of IDF/SDF between 1:1 and 2:1 to yield maximum health benefits. [11]Berry pomace widely exceeds the 2:1 IDF to SDF ratio usually (Table 1). In addition, the fiber pomace retains compounds with interesting characteristics such as polyphenols with antioxidant capacity bound to the cell wall. Thus, according to Saura-Calixto et al. [56] the pomace fiber can be considered as an antioxidant dietary fiber because of its capacity to act as a carrier of phenolic compounds with a potential antioxidant effect.

The fat content ranges from 0.67 to 20.21% in the different berry pomaces, being the lowest for blueberry and the highest for blackcurrant. The fat content will depend mainly on the seed content, differing between berries and pomace processing conditions. Protein varies between 2.20 and 15.89%, with cranberry having the lowest values and goldenberry the highest.

Table 1. Proxymate composition of dried berry pomaces.

Berry	*Dry weight (% w/w)*	*Protein (% in DM)*	*Fat (% in DM)*	*Carbohydrates (% in DM)*	*Ash (% in DM)*	*TDF (% in DM)*	*SDF (% in DM)*	*IDF (% in DM)*	*References*
Bilberry	94.20	17.00	-	-	1.23	58.90	6.90	52.00	[37,38]
Black chokeberry	93.80–94.7	6.44–8.40	4.10–4.49	45.12	1.80–1.95	42.00–63.50	-	-	[39,40]
Black currant	89.21–96.80	11.80–17.00	2.0–20.21	2.20–14.90	1.95–4.10	20.18–90.8	3.97	55.16	[29,37,41–43]
Blackberry	95.50	10.80	10.80	-	1.70	60.30	2.80	-	[44]
Blueberry	53.62–81.45	4.67–12.03	0.67–5.43	60.94–87.05	0.95–2.06	26.15–38.50	0.97–8.20	48.95–53.8	[26,27,44–48]
Chokeberry	90.21–97.28	5.97–10.77	3.61–5.15	28.88	1.92–6.94	21.79–95.77	7.04	52.46	[29,42,43,49,50]
Cranberry	68.37–71.53	2.20–5.76	2.50–12.00	88.78–91.25	0.70–1.10	-	0.75–5.70	57.7–65.5	[26,27,48,51]
Goldenberry	94.13	15.89	13.72	61.00	3.50	16.74	-	-	[10]
Gooseberry	94.95	12.40	10.93	16.26	3.40		7.04	49.56	[29]
Raspberry	87.80	10.00	21.84	-	4.10	59.50	0.34–2.30	38.13–57.2	[27,52]
Red currant	94.82	11.76	14.23	12.65	3.00		7.00	51.08	[29,53]
Rowanberry	97.31	7.09	3.97	18.71	2.84		7.68	59.49	[29]

Therefore, the importance of pomace composition mainly lies in its fiber content (mostly insoluble fiber) and in its phenolic compounds.

Polyphenols

Polyphenols from berry pomaces engage in a wide range of biological and antioxidant activities. Phenolic composition is different for each class of berry and also may vary within the same species but between cultivars [57,58] and years of harvest seasons.[41] To determine the phenolic content of polyphenols and their antioxidant capacity, there are different methods usually based in UV/VIS spectrophotometric methodologies. The most widely spectrophotometric methods used for phenolic content determination are the Folin Ciocalteau and Folin-Denis, which are antioxidant assays based on electron transfer that measures the total reducing capacity of an antioxidant sample.[59] Table 2 shows the total phenolic content values from different berries determined using this method.

However, these spectrophotometric methods only give the total phenolic content and do not identify the individual compounds. Therefore, more sensitive and specific procedures are needed. Gas chromatography (GC) and High-performance liquid chromatography (HPLC) are two of the most widely applied methods for phenolic identification and quantification. HPLC is a simple and highly efficient procedure, which is sensitive and specific, but it is very time consuming and requires special expertise and equipment. Rodríguez-Werner et al. [49] analyzed the chokeberry pomace phenolic composition. They found that the major compounds were polymeric procyanidins and glycosylated anthocyanins such as cyanidin-3-*O*-galactoside and phenolic acids such as neochlorogenic and chlorogenic acid. Likewise, Sojka et al. [39] obtained similar results for black chokeberry pomace, showing proanthocyanins (polymeric molecules) were the most abundant compounds, followed by the anthocyanins such as cyanindin-3-*O*-galactoside y cyanidin-3-*O*-arabinoside.

These polyphenols also present antioxidant capacity, which can also vary depending on the type of processing. The methods used for measuring the antioxidant capacity are also based in UV/VIS spectrophotometric methodologies, being the most used: ABTS (Trolox equivalent antioxidant capacity), [45,46,50,62,63,68] DPPH, [41,45,46,53,58,61,63,65,67] and FRAP (ferric reducing antioxidant power).[26,63,64,68] These antioxidant capacity assays are based on single electron transfer reactions.

The antioxidant capacity derived from the phenolic compounds confers them certain characteristics, such as antimicrobial capacity.[69–72] However, the antimicrobial effect is not only due to the bioactive composition, the low pH values of pomace also affects the microbiological survival.[73]

Another important property derived from the antioxidant activity of polyphenols is the ability to reduce the lipid oxidation of food.[74] Food oxidation can be caused by oxygen free radicals or reactive oxygen species, and can alter the food texture, flavor, or odor, as well as reduce the shelf life. The antioxidant capacity of polyphenols is related to their ability to scavenge these free radicals. Different authors have studied the effect of berry pomace used as a natural ingredient to elude these oxidation processes.[75,76]

Furthermore, berries can have a prebiotic effect, due to the polyphenolic compounds capacity to improve the gut health favoring the growth of beneficial microorganism.[14,77] However, this effect has not been studied in pomaces yet.

Techno-functional characteristics of berry pomace

Berry pomace is usually processed to obtain a powder. As described before, the pomace is first dried to avoid microbial spoilage and once it is dried, it is usually milled to obtain a powder.

Berry pomace powder has specific techno-functional properties, which must be known before incorporating pomace into food products. Several authors have studied different techno-functional properties of berries such as water and oil absorption, swelling and foaming capacity, and bulk density. These properties influence other important characteristics of the final product, e.g.: water absorption has a key role on texture quality, and oil absorption is significant in terms of consistency and bulking.

Reißner et al. [29] observed that low water binding capacity was related to small particle sizes, whereas larger surface areas favored water adsorption; however, the oil absorption capacity was related to particle porosity rather than chemical composition or molecular affinity to oil. Mokhtar et al. [10] obtained similar values to Reißner et al. [29] for water and oil absorption in goldenberry pomace, being the oil absorption lower than water absorption, which they attributed to the higher number of hydrophilic groups capable of binding water, and to the soluble dietary fiber content that possess high water absorption capacity. In addition, Gouw et al. [27] explained that the property of oil absorption could be due to the fiber-fiber interactions that would be expose the hydrophobic surface to adsorb oil.

Swelling capacity is highly related to water absorption, thus lower water absorption will be in accordance with low swelling capacity. Reißner et al. [29] and Moktar et al. [10] obtained similar results for this parameter. Mokhtar et al. [10] also observed good foaming capacity and stability due to the berry pomace protein content, which formed a continuous cohesive film around the air bubbles in the film; this property mainly depended on pH, viscosity, and processing methods. Berry pomace also has low bulk density, which evaluates the suitability for its incorporation in food formulations.[10]

Thus, berry pomace can be used in the formulation of a wide range of food products; however, it is necessary to consider its techno-functional characteristics, which will affect rheological, textural, and sensory properties, as well as the nutritional value.

Uses of berry pomace in food products

Functional foods can be classified as: fortified products (increased content of existing nutrients), enriched products (incorporation of new nutrients), altered products (replacement of existing nutrients by others with beneficial functions), and enhanced commodities (alteration of nutrient composition by changes in the raw commodities).[78] In all the cases using pomace in the formulation influences their nutritional, physicochemical, or organoleptic characteristics. There are different ways of incorporating the pomace in food. It can be incorporated as a fresh or dried ingredient, and sometimes, an extract of the phenolic compounds is obtained from the pomace and then added to the food.

As phenolic compounds are bound to the cell wall, using a polyphenolic extract from the berry pomaces for specific purposes is interesting. Thus, a high concentration of bioactive compounds excluding other compounds such as dietary fiber and proteins, is obtained. Polyphenols are soluble in water and in alcohol due to its conformation and chemical structure; consequently, most extraction methods use water, ethanol, or their mixtures as solvents. The main extraction methods are mentioned in Table 3.

Traditional methods of extraction are mostly based on using high amounts of solvents that generates large amounts of waste that can be hazardous. These methods use heat to improve mass transfer and usually long extraction times that could have a risk on bioactive thermal degradation. To overcome this problem and mitigate the limitations associated to these extraction methods, innovative technologies are being investigated to meet the ongoing consumer demands for minimally processed products, and to meet the requirements of a green extraction concept. The main extraction methods used for berry pomace extraction are summarized in Table 3.

Berry pomace in bakery products

In the last years, the bakery industry has been developing products toward the functional food market; these products provide an ideal matrix to introduce functional ingredients with potential health benefits, supplying a product capable of satisfying consumer demands in terms of appearance, taste,

Table 2. Total phenolic content of different berry pomaces.

Berry	Extraction conditions	Result	Unit	References
Bilberry	MetOH 70% + 1% trifluoroacetic acid	4552 ± 116	mg GAE/100 g DM	[34]
Black currant pomace	Acetone & sonication	2004 ± 17	mg GAE/100 g of sample	[60]
	EtOH 92%; solid:solvent 1:2 (w/v); 30 min, room temperature, dark	5530 ± 1080	µmol GAE/100 g FW	[53]
	MetOH:water:formic acid at 50:48:2 v/v; solvent:solid 10:1; sonication 5 min and dark 15 min	2077.0 ± 44.4	mg/100 g pomace	[41]
	MetOH:water:formic acid at 50:48:2 v/v; solvent:solid 10:1; sonication 5 min and dark 15 min	2241.6 ± 81.9	mg/100 g pomace	[41]
Blackberry pomace	EtOH 50%; 1:10 solid:solvent (w/v); 20 C 48 h	3967.7 ± 21.43	mg GAE/100 g DM	[61]
	EtOH:water 1:1; 1:10 solid:solvent (w/v); 20 C 48 h	2828.66 ± 12.1	mg GAE/100 g DM	[61]
	MetOH 75% (1% HCL 1 N); solid:solvent 1:5; 12 h 25 C	1699.62 ± 174.50	mg GAE/100 g DM	[62]
	MetOH/water (50:50, v/v); 1 h, room temp + acetone/water (70:30, v/v); 1 h, room temp	4016.43 ± 13.44	mg GAE/100 g DM	[63]
Blueberry pomace	MetOH 80%; solid:solvent 1:100 w/v	3.02 ± 0.12	mg GAE/100 g DM	[46]
	MetOH 75% (1% HCL 1 N); solid:solvent 1:5; 12 h 25 C	1954.54 ± 177.82	mg GAE/100 g DM	[62]
	EtOH 70%+ glacial acetic acid 0.5%; 24 h 4 C in dark	2694 ± 29	mg GAE/100 g DM	[64]
	MetOH 70%; solid:solvent 1:10; 60 min	3113 ± 34	mg GAE/100 g DM	[26]
	HCl 1% in metOH; solid:solvent 1:30 (w/v); 60 min, room temperature	2920 ± 58	mg GAE/100 g sample	[65]
	HCl/metOH/water (1:80:10 v/v); solid:solvent 1:20; 2 h, room temperature	10,234 ± 244	mg GAE/100 g DM	[47]
Blueberry extract	EtOH 80%; solid:solvent 1:5 (w/v); 1 h	7201 ± 193	mg GAE/100 g DM	[26]
Chokeberry pomace	MetOH 75% + Formic acid 0.1%	6310 ± 50	mg GAE/ 100 g FW	[66]
	MetOH 60%:water:formic acid (85:12:3)	3100 – 6300	mg/100 g wb	[50]
Cranberry pomace	MetOH 70%; solid:solvent 1:10; 60 min	2487 ± 66	mg GAE/100 g DM	[26]
Cranberry extract	EtOH 80%; solid:solvent 1:5 (w/v); 1 h	5435 ± 85	mg GAE/100 g DM	[26]
Green currant	EtOH 92%; solid:solvent 1:2 (w/v); 30 min, room temperature, dark	1710 ± 290	µmol GAE/100 g FW	[53]
Raspberry extract	MetOH 80%; 60 min, shaking	14,934 ± 401	mg GAE/100 g dry extracts	[58]
	MetOH 80%; 60 min, shaking	9388 ± 445	mg GAE/100 g dry extracts	[58]
	MetOH 80%; 60 min, shaking	13,243 ± 457	mg GAE/100 g dry extracts	[58]
	MetOH 80% y acetic acid 0.05%	4370 ± 202	mg GAE/100 g dry extracts	[67]
	MetOH 80% y acetic acid 0.05%	2630 ± 128	mg GAE/100 g dry extracts	[67]
Red currant	MetOH 75% (1% HCL 1 N); solid:solvent 1:5; 12 h 25 C	3446.59 ± 805.17	mg GAE/100 g DM	[62]
	EtOH 92%; solid:solvent 1:2 (w/v); 30 min, room temperature, dark	2050 ± 710	µmol GAE/100 g DM	[53]
Red raspberry pomace	MetOH 75% (1% HCL 1 N); solid:solvent 1:5; 12 h 25 C	2014.66 ± 100.91	mg GAE/100 g DM	[62]
Sea buckthorn north pomace	EtOH 92%; solid:solvent 1:2 (w/v); 30 min, room temperature, dark	1360 ± 110	µmol GAE/100 g FW	[53]
Sea buckthorn south pomace	EtOH 92%; solid:solvent 1:2 (w/v); 30 min, room temperature, dark	880 ± 60	µmol GAE/100 g FW	[53]
White currant pomace	EtOH 92%; solid:solvent 1:2 (w/v); 30 min, room temperature, dark	2470 ± 440	µmol GAE/100 g FW	[53]
Yellow raspberry extract	MetOH 80%; 60 min, shaking	10,124 ± 323	mg GAE/100 g dry extracts	[58]

*GAE: galli acid equivalents; DM:dry matter; FW:fresh weight; wb:water basis.

and texture.[2,11,99] Pomace incorporation into bakery products is simple and quick to manage, which is why it has aroused great interest, especially in products made with white flour, such as white bread, cookies, cakes, or muffins. However, berry pomace incorporation leads to certain changes in the food, thus it is useful to know its impact on dough technological properties to obtain a good integration of the by-product into bakery products; achieving greater acceptance of the product by the consumer.[100–102]

From a technological viewpoint, the composition of the pomace, as well as its ratio of insoluble and soluble fiber (IDF/ SDF) influences the rheological behavior of the dough of bakery products, the development time, and the rate of water absorption in the mixture.[11] Specifically, berry pomaces contain a higher insoluble fraction (cellulose, hemicellulose, and lignin) than soluble, which causes alterations, such as the reduction in the hydration rate of wheat proteins due to the porosity of insoluble fiber that facilitate the water absorption. This effect leads to a weaker gluten network, which causes detrimental effects for the creation of a well aerated structure, partly due to a decrease in the air retained by the dough, which results in a firm, less fluffy texture and a reduction in volume in the product.[11,103,104]

Bread

Bread is a product consumed daily, and it has seen a growing interest in incorporating functional ingredients, since it is a key vehicle for the contribution of fiber and bioactive compounds to the population. However, good acceptance by the consumer must be guaranteed to compete with conventional or traditional wheat bread.[105,106]

Struck et al. [102] partially replaced wheat flour (10, 20, or 30%) with dried blackcurrant pomace to analyze the behavior of model bread doughs. They observed that increasing quantities of the by-product caused an increase in dough water absorption, dough development time, and structural strength when the model doughs were baked, leading to the disruption of the gluten matrix. They concluded that lower substitutions (10%) give doughs with desirable characteristics, whereas higher substitutions would need the use of additives to increase the gluten strength. Likewise, Alba et al.[107] not only observed the effects of flour replacement with blackcurrant pomace (5, 10, 15, or 20% w/w) in bread dough, but also in the final baked bread. Incorporating berry pomace decreased the extent of gluten hydration resulting in stiffer doughs, modifying the morphology of gas bubbles, and resulting in breads with lower specific volume and harder crumb structures.

Furthermore, Martins et al. [105] used the fiber rich fraction from elderberry pomace as fortification in bread formulations (5, 7, and 10%, added in % wheat flour). The pomace addition caused a higher percentage of small cells, but lower cells distributed in the medium. The authors observed that higher acceptability was obtained for breads with a 7% pomace addition when compared to the control. Thus, they concluded that bread sensory characteristics were influenced by adding a fiber rich fraction from elderberry pomace.

Table 3. Extraction methods for obtaining berry pomace extracts.

Extraction methods		References
Traditional methods		[79–82]
Novel extraction processes	Supercritical fluid extraction	[79,82–85]
	Microwave-assisted extraction	[86]
	Ultrasound-assisted extraction	[63,87–91]
	Pulse electric field extraction	[92]
	High pressure extraction	[93–95]
Green chemistry-based extraction techniques	Enzyme-assisted extraction	[94,96–98]

Reiβner et al. [108] studied blackcurrant pomace addition into bread, and highlighted the importance of considering the hydration of dietary fiber, which is often neglected in bakery products because the degree of hydration could substantially affect the bread-making process. The pre-hydration of pomace affected the water absorption of dried pomaces; the hydrated fiber had less competition for water, allowing the correct gluten network development enhancing the final bread properties.

In terms of physical properties, the pomace incorporation into breads mainly lead to textural changes and these changes were also appreciable in sensory analysis. The physical and sensory properties of doughs and breads have been studied by different authors, but more studies are needed to understand how the pomace incorporation affects the nutritional quality in terms of bioactive compounds such as fiber and phenolic compounds.

Other bakery products

Incorporating berry pomace in different bakery products such as cookies, muffins, or cakes has also been studied.

Cookies are widely consumed baked foods; they usually contain flour, sugar, and some oil or fat. They may include other ingredients such as raisins, oats, chocolate chips, nuts, fiber, etc. A way of incorporating fiber is using berry pomace. For example, Górecka et al. [109] incorporated raspberry pomace in short crust cookies as a partial replacement (25 and 50%) of flour to obtain cookies with an added health claim for fiber content to improve the nutritional profile. They obtained cookies with high contents of fiber without a negative influence on organoleptic properties.

The pomace has not only been used for improving the nutritional profile but also for the different physicochemical characteristics it can provide to the cookies. In the study carried out by Tańska et al. [110] the pomace of different fruits such as blackcurrant and elderberry, among others, was used in cookies formulations. These pomaces were used at different concentrations (5, 10, 15, 20, 25, 30, and 50% w/w) as a flour replacement. Specifically, 20% blackcurrant pomace stood out for its high anthocyanin content, contributing significantly to the total phenol content in cookies. Regarding the characteristics of the cookies and compared to controls, adding pomace maintained their round shape, diameter, and thickness. They showed a greater hardness, as the percentage of replacement increased, although the organoleptic evaluation showed that a more crunchy and hard texture was still desirable by the panelists. Furthermore, the inhibition efficiency of the formation of free radicals, which indicates the oxidative stability of the lipid fraction, was evaluated, showing the oxidation of lipids was negligible when pomace was used. The antioxidant effect of berry pomace extracts has been also studied. Bialek et al. [75] used a chokeberry polyphenolic extract instead of the pomace in cookies, and observed that it had a significant impact decreasing oxidation levels even during the storage period in which oxidative changes can occur. Thus, chokeberry polyphenolic extract can extend the shelf life of cookies in terms of lipid oxidation. However, high contents of this extract can give undesirable sensory characteristic, such as taste, decreasing the consumer acceptance.

Therefore, besides the changes in physicochemical properties, it is important to assess if incorporating berry pomaces has a detrimental effect on sensory characteristics. Curuchet et al. [111] evaluated the sensory attributes of cookies enriched with antioxidant fiber from blueberry pomace (37.14 g / 100 g dough, D.M.). They found that even though the consumers were positively influenced by the appearance, most consumers negatively ranked the acceptability when the cookies were tasted. Thus, if pomace fiber is used as an ingredient, the formulation needs to be optimized considering the consumers' appeal.

Other widely consumed sweet bakery products are cakes and muffins, which are mainly made with eggs, flour, oil, and sugar, sometimes leavened with baking powder. Quiles et al. [112] showed the effect of using dried pomace of black currant and chokeberry berries as a substitution of flour, fat, or sugar in cakes. The substitution of the three components had an influence on dough and cake properties, because they all play a key role in developing the product. Sugar replacement caused a premature gelatinization of the starch, reducing the competition for water, causing a higher cake dough viscosity, giving rise to a harder final cake, and with a greater formation of small alveoli in the crumb. Flour replacement led to softer cakes with an increase in the size of crumb alveoli, which could be related to the decrease in the capacity to retain gas. Fat replacement gave doughs and cakes with intermediate values for cake texture, and number and size of alveoli. The *in vitro* starch digestibility was also studied and cakes with flour replacement showed the lowest hydrolysis and glycemic indices, whereas fat replaced cakes showed the highest values.

Thus, incorporating pomace in cakes and muffins possesses some aeration problems in the dough that affects the final characteristics of the product. Some alternatives that have been studied to improve this problem are the use of different leavening agents, such as encapsulating bicarbonate with citric acid or sodium acid pyrophosphate. The combination of pyrophosphate with bicarbonate improved the incorporation of air into the product formulated with pomace, leading to larger gas alveoli and a smoother texture.[103]

Another alternative to aeration problems is the use of pregelatinized flours. Diez-Sánchez et al. [113] substituted 50% of wheat flour for extruded wheat flour in muffins formulated with dry blackcurrant pomace at 20% w/w. This allowed the formation of a more compact and consistent network with a more homogeneous fat distribution, and the muffins did not present differences in texture properties or consumer acceptance compared to a standard formulation. Despite the benefits of pregelatinized flour on texture, it can increase the glycemic index, which can be a negative effect; however, this increase is counteracted by the inhibitory effect of berry pomace on digestive enzymes such as α-amylase.[114]

Other studies are related to the optimization of the production parameters to obtain a product with optimal characteristics. Mildner-Szkudlarz et al. [115] used European raspberry and American cranberries dried pomaces as wheat flour replacers (10 and 20% (w/w)) in muffins and studied different baking conditions and their effect on microstructure, texture, and phenolic content. The baking conditions affected the texture and the polyphenol content. Moreover, the optimal baking conditions were 180°C for 20 min, when the best texture properties were obtained without excessively affecting the phenolic content. Gornas et al. [116] also studied how baking temperature (140, 180, and 220°C) and type of oven (conventional or halogen) affected the stability of muffins enriched with blackcurrant and raspberry pomaces, among other fruit pomaces. The muffins remained in the oven until the temperature inside the muffins reached 107°C. An increase of free ellagic acid content was positively correlated with the baking time, which resulted from thermal hydrolysis of ellagitannins and ellagic acid glycosides. Short baking time (14 min) combined with the highest temperature (220°C) in the conventional oven had the best effect on polyphenol preservation. Finally, the reformulated muffin did not differ from the control in terms of overall acceptability.

Gluten-free products

Gluten-free bakery products on the market entail a higher cost for the consumer compared to their gluten-containing counterparts. These products are usually reformulated with refined flours and starches, thus sacrificing its nutritional profile in terms of fiber content.[117] Despite being numerous investigations on new alternatives to replace refined flours and starches, investigation is still necessary to obtain products with physicochemical, nutritional, and sensory characteristics acceptable to the consumer. A good alternative is the reuse of low-cost ingredients, such as fruit by-products, which will contribute to improve nutritional and functional properties of gluten-free products.[117]

Pomace from blueberry and raspberry were incorporated in substitution of 30% of flour in gluten-free cookies formulated by Šarić et al. [117] Even though the addition of pomace caused changes in the properties of the dough and appreciable sensory changes for smell, taste, and appearance, the overall acceptability was positively ranked. Regarding the nutritional profile of the cookies, notably, the enrichment with berry pomaces provided between 6.92 and 7.45 g/100 g of fiber, depending on the berry used, but the fiber content was higher than 6 g per 100 g, which makes it possible to label the product as "high in fiber," thus satisfying around 30% of the dietary reference intake for dietary fiber, which is 25 g/day.

In another study carried out by Gagneteen et al.[118] blackcurrant pomace was incorporated in a gluten-free chocolate cookie formulation. Their results showed that the blackcurrant pomace gave gluten-free cookies with higher fiber content and with interesting amounts of polyphenolic compounds without affecting the acceptability of the final product. In addition, they suggested that if consumed, part of the phenolic compounds reach the large intestine where they can exert their antioxidant activity.

A similar cookie product is crackers, which are savory or salty flat biscuits usually formulated with wheat flour and different gluten-free flours. Schmidt et al. [119] incorporated dried blueberry pomace to a formulation as a total or partial substitution of gluten-free flours. This incorporation restricted the development of the protein network due to the alterations caused by fiber interactions, which with the low starch content resulted in low extensible doughs and soft crackers.[119] However, the general acceptance was not affected by the pomace incorporation.

Therefore, although the pomace provides an extra fiber content in products with a deficiency in this component, it must be considered that it will affect the characteristics of the final dough, giving less extensible and weaker doughs. However, these products still had good acceptability by the consumers, besides an increase in their nutritional quality compared to gluten-free cookies present in the market. Consequently, it could be said that the pomace of berries can be incorporated in gluten-free doughs to provide an ingredient of greater value in both quality and health, improving the nutritional quality of common gluten-free bakery products.

Berry pomace in meat products

One of the greatest factors for deterioration in meat products is the oxidation of lipids, limiting their quality and acceptability because it causes rancidity, modification of the texture, undesirable odors, nutritional losses, and formation of detrimental compounds.[76] In addition, if the meat is heat-treated (e.g. cooked), physicochemical changes are accelerated, causing a greater susceptibility of the meat to undergo oxidative reactions, with the consequent changes in the flavor that could eventually pose problems on the consumers acceptability.[73,76,120]

Specifically, the minced meat used to make hamburgers is often more prone to oxidative changes than the entire piece, since it has a greater contact surface exposed to the oxygen in the air, which causes its deterioration. These reactions modify the color and texture, and cause undesirable odors and nutritional losses. In addition, toxic compounds can be formed, reducing the nutritional quality. This toxic compounds, such as hydroperoxides, aldehydes and oxyterols implicate a harmful effect on health.[121] Synthetic antioxidants easily decompose at high temperatures and there is a potentially toxic effect in their use, thus the meat industry has looked for new alternatives to synthetic antioxidants,[122] such as natural antioxidants derived from fruits or by-products like pomace.[123,124]

Peiretti et al. [76] analyzed the effect of blueberry pomace at a concentration of 1 and 2% w/w on oxidative stability of pork patties stored in refrigeration for 7 days. The pomace-pork patties showed a decrease in some volatile compounds, such as hexanal, indicating that lipid oxidation was lower than the control without pomace. This could be due to the high content of phenolic compounds of berry pomaces and their intense antioxidant activity, capable of stabilizing lipid oxidation, prolonging storage for 7 days. Other studies with pork meat, used frozen blackberry extract to reduce meat oxidation caused by light, heat, enzymes, metals, and microorganisms [125]; using the extracts inhibited lipid oxidation, blocking the formation of free radicals. Furthermore, the formation of undesirable flavors and colors (metmyoglobin), which could damage the organoleptic characteristics of the meat, was avoided in the final product.

These studies show that using pomace can be a potential natural alternative for the substitution of synthetic phenolic antioxidants, allowing preservation of the quality of meat products for a longer time.

The antimicrobial properties of pomaces have been also widely explored. This property is likely to be caused by multiple mechanisms and synergies due to its composition. Some of the proposed mechanisms of inhibition include damage of bacterial cell membrane, inhibition of extracellular microbial enzymes and damage of structural proteins.[126] There are some preliminary *in vitro* studies related to using pomace to reduce the microbial growth of typical meat pathogens like *Campylobacter jejuni* [127] or *Escherichia coli* O157: H7, *Salmonella enterica*, and *Listeria monocytogenes*.[73] Salaheen et al. [127] showed the effect of extracts from blackberry and bilberry pomaces on the growth and pathogenicity of *Campylobacter jejuni*. The results showed that both extracts had a potential bactericidal effect; the blackberry extract had a long-term bactericidal effect extended until after 72 h, whereas the blueberry extract lost effect after 24 h, being the Minimum Inhibitory Concentration (MIC) values of 0.6 mg/mL GAE and 0.4 mg/ml GAE for blackberry and blueberry pomace extracts respectively. Consequently, it was shown that blackberry and blueberry pomace extracts have a high potential in the control of pathogens in meat and meat products, acting as natural and organic preservatives.

Četojević-Simin et al.[67] studied the potential of two raspberry cultivars (Meeker and Willamette) to determine the MIC values against reference and wild strains. They found that MIC values ranged from 0.29 to 0.39 and 0.29 to 0.59 (Meeker), and from 0.29 to 0.59 and 0.29 to 0.59 (Willamette) against Gram-positive and Gram-negative bacteria, respectively. Thus, the raspberry pomace extracts, regardless of the cultivar, inhibited growth of all tested strains for both Gram-positive and Gram-negative bacteria, meaning that the antimicrobial activity was neither strain- nor species-dependent.

Yin Lau et al. [73] investigated the use of the ethanolic extract of lingonberry pomace for the inhibition of pathogens present in meat such as *Escherichia coli* O157: H7, *Salmonella enterica*, and *Listeria monocytogenes*. At the highest concentrations in the study, total inhibition was achieved, which the authors attributed to a combined effect of the acidic pH of the pomace and the high content of bioactive phenolic compounds.

Tamkutė et al. [128,129] studied the effect of cranberry water and ethanol extracts and defatted chokeberry on bacterial cultures – *Listeria monocytogenes, Brochothrix thermospacta, Pseudomonas putida*, lactic acid bacteria, aerobic mesophilic bacteria – and on pork meat products – pork slurry, burgers, and cooked ham. Both cranberry water and ethanol extracts effectively inhibited the growth of tested bacteria. Using the ethanol extract was also effective in the meat products studied. It was also effective for the inhibition of malondialdehyde, which is a product from the lipid oxidation, and did not have a severe impact on some of the physicochemical properties of the meat products studied, although it provoked color changes that did not affect the overall acceptability.

In the study by Kryževičūtė et al. [130] extracts of raspberry pomace were obtained using supercritical CO_2 and pressure liquid extraction (PLE) and added to beef burgers. They observed that using extracts isolated with PLE can be a way to inhibit lipid oxidation during storage and to reduce the spoilage microorganism load in meat. Moreover, its incorporation in burgers did not have a negative effect on sensory attributes and thus could be a promising natural additive for increasing the stability of meat products. Regarding defatted chokeberry extract, the ethanolic extract (2%) inhibited bacteria in all the meat products studied; thus, it could be a potential natural antimicrobial ingredient extending the shelf life of meat products.

In the described studies, an antimicrobial effect both in *in vitro* studies and in meat products has been proven. Therefore, and due to the growing interest that the consumer has toward natural, organic food products without added chemicals, all this information is of special importance, since the berry pomace or its extract could be used as promising antimicrobial agents.

Berry pomace has also been investigated regarding its potential use as a promoter of starter cultures in meat. The fermentation of meat is an ancient form of preservation; during fermentation, certain autochthonous microorganisms grow, allowing the meat to acidify, inhibiting the growth of spoilage/pathogenic microorganisms. However, exogenous microorganisms are often added to achieve certain biochemical characteristics that the native flora cannot achieve; they are the so-called starter cultures. Its function usually is to cause an accelerated drop in pH, through the production of lactic acid, favoring the development of flavor, texture, and microbiological stability of the final product. In the study carried out by Yin Lau et al. [73] the extract of cranberry pomace improved the yield and growth rate of some microorganisms used as meat ferments, such as *Lactobacillus* and *Pediococcus* spp. Thus, the phenolic compounds present in berry pomaces can stimulate the growth of meat starter cultures.

In conclusion, the addition of pomace or its extract in different meat products has shown an antioxidant effect, sequestering the oxidants species, and delaying the formation of toxic products, due to the polyphenols in their composition. It also has an antibacterial effect against spoilage and pathogenic microorganisms and can be a substrate for the growth of starter cultures. Likewise, the high dietary fiber content provides the meat with greater retention of moisture and fat, which is a positive influence on the cooking properties. This makes it possible to extend the useful life of the product and reduce the environmental impact produced by meat waste.

Berry pomace in dairy products

Numerous studies indicate the fundamental role of dairy products in the world's diet's population. Yogurt is one of the most consumed dairy products, both for its organoleptic and nutritional value. Yogurt is easily digested, providing a bioaccessible matrix to incorporate bioactive compounds, thus obtaining a positive effect on health.[131] Using pomace in its formulation made it possible to fortify the product and provide it with suitable characteristics to consider it an excellent functional food.[132]

Several authors have studied the antioxidant effect of berry pomace when incorporated into yogurt. In the study carried out by Raikos et al. [132] the incorporation of blackcurrant pomace extract was compared with a Gaultheria shallon berry extract in yogurt formulations. Incorporating blackcurrant pomace at 20% w/w caused an increase in total phenols in all yogurts stored for 4 weeks, although during storage there were fluctuations in the phenolic content. These fluctuations could be due to the release of amino acids with phenolic side chains, such as tyrosine, which could increase the phenol content when the proteolysis of milk proteins occurred [132] or to the interactions of polyphenols with milk proteins forming insoluble complexes that could decrease the phenolic content.[133] Regarding the antioxidant capacity, a decrease was observed when Gaultheria shallon extract was used, whereas using blackcurrant pomace increased antioxidant capacity was maintained during storage of 4 to 5 weeks.[132]

Beyond the antioxidant capacity of berry pomace, an *in vitro* antidiabetic effect was observed by Ni et al. [134] These authors used 20% w/w extracts of blackcurrant pomace to reformulate the original composition of yogurt and study its possible antidiabetic effect. The extract promoted the gradual release of bioactive peptides during the storage of the yogurt, which inhibited the α-amylase and α-glucosidase enzymes, delaying the release of monosaccharides from complex carbohydrates. The possible inhibition mechanism could be because the polyphenols present in pomace bind to the active site of the enzyme, preventing its action.[114] These findings suggest that yogurt with extracts can help blood glucose regulation, although further research is needed to evaluate the bioactivity of peptides, and their potential as α-amylase and α-glucosidase enzymes inhibitors.[134]

Besides using pomace or its extract as antioxidant or antidiabetic, it has been used for other purposes. For example, Diez-Sánchez et al. 135 studied the effect of different processing conditions with high hydrostatic pressures (200–500 MPa; 1–10 min) in milkshakes with chokeberry pomace, to obtain the treatment that provided a higher phenolic content and a higher antioxidant capacity with the lowest survival of the pathogenic microorganism *Listeria monocytogenes*. The treatment that obtained the best results was at 500 MPa for 10 min and with a pomace concentration of 10%.

Thus, berry pomace can be a great option in dairy products as an ingredient that could improve its nutritional value and provide beneficial properties (antioxidant, antidiabetic . . .).

Berry pomace in snack foods

Snack products are widely consumed but have low nutritional value. Thus, Drożdż et al. [136] formulated extruded puffed corn snacks with chokeberry and blackcurrant pomace to obtain snacks with an enhanced nutritional value, increasing the total phenolic content. The pomace incorporation affected the expansion rate, the water absorption, and solubility index, giving lower values by increasing proportions of pomace. They concluded that the puffed snacks with berry pomace addition can be an interesting functional food due to its high content of phenolic compounds and antioxidant capacity. In another study carried out by Mäkilä et al.[137] snacks were formulated with blackcurrant pomace (30%), cereal materials (40%- oat flour, barley flour, or oat bran), potato starch (30%), sugar, and salt. The results showed that the snacks had desirable physicochemical characteristics, but with the need to improve sensory characteristics. The authors observed that maintaining the berry-like characteristics was important for consumers.

Wang et al. [138] studied the effect of cranberry and blueberry pomaces incorporation on the expansion characteristics of corn starch extrudates. The expansion was influenced by several factors such as the pomace level incorporation, and specifically, the authors observed that pomaces with high soluble dietary fiber led to higher expanded extrudates. They concluded that the different results were due to the interactions between the pomace components and the starch.

Therefore, incorporation of berry pomace in extruded snacks can be a good alternative for developing new functional foods. Its incorporation did not affect the properties negatively, but the sensory aspects should be improved.

Other applications of pomace

In recent years there has been a trend toward natural polymers based on food products to replace non-biodegradable plastics. Compounds are incorporated into these polymers to turn them into active packaging material; besides the primary effect as a preservative, they include antioxidant or anti-microbial activities. Staroszczyk et al. [139] used the aqueous extracts from rowanberry, blueberry honeysuckle, and chokeberry pomaces to formulate fish gelatin film. They observed an antioxidant, and an antimicrobial effect of berry pomace extracts due to its content in polyphenols, as well as improved mechanical and water barrier properties.

Other authors also studied the incorporation of a pomace extract as a new film-forming material. Park and Zhao[140] developed films by adding cranberry pomace extract to provide a unique flavor and color. Singh et al. [141,[142]] developed starch-based edible packaging films incorporating blueberry pomace powder and investigated the feasibility of using these films for food packaging.

Pomace has not been only used as antimicrobial or antioxidant material in film preparations, but also as a natural indicator in bio-based polymer packaging. Kurek et al. [140] used blueberry and red grape skin pomace extracts as indicators of chicken meat quality in a novel bio-based polymer packaging. The extracts worked changing its color; the results showed there was a change in color film in correlation with pH changes of spoiled meat samples. Thus, the authors developed a colorimetric indicator of changes in perishable food products were changes in pH determine the spoilage of the product.

Therefore, berry pomaces and their extracts can be used as carriers of bioactive compounds not only for functional food production but also for developing active packaging or even a colorimetric bio-based sensor.

Conclusions

Using by-products rich in bioactive compounds to formulate foods is an emerging topic in food science research. The current review surveys the usage of berry pomace in bakery, dairy, and meat products, snacks, and some alternative uses like packaging films. From a nutritional viewpoint, the pomace provides food with important benefits, because it improves antioxidant capacity, microbiological stability, nutritional profile (fiber content) and avoids lipid oxidation. However, the addition of pomace in food formulation may result in appreciable changes in color, e.g. in bakery products originally formulated with white flour, as well as in texture, flavor and odor. Moreover, some processing conditions, as temperature or pressure, can affect phenolic compounds and antioxidant capacity; therefore, new strategies can be needed to use this by-product. Despite of that, it can be included in a wide range of foods at significant levels maintaining consumer acceptability. The valorization of berry by-products can offer an added value to food products, contributing to a more sustainable food chain from an environmental viewpoint.

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ORCID

Isabel Hernando http://orcid.org/0000-0002-3322-935X

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