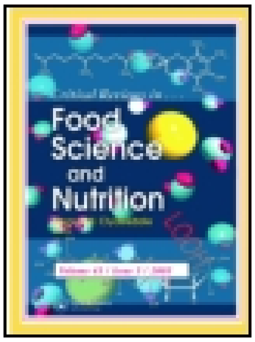

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REVIEW

High value-added compounds from fruit and vegetable by-products – Characterization, bioactivities, and application in the development of novel food products

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ABSTRACT
Fruit and vegetable processing industry is one of the relevant generators of food by-products, which display limited commercial exploitation entailing economic and environmental problems. However, these by-products present a considerable amount of dietary fiber as well as bioactive compounds with important biological activities such as antioxidant and antimicrobial properties. Therefore, the international scientific community has considered the incorporation of their extracts or powders to preserve or fortify food products an area of interest, mainly because nowadays consumers demand the production of safer and health-promoting foods. In the present review, several statistical and other relevant data concerning the increasing generation of fruit and vegetable by-products (FVB) are critically analyzed and presented. Next, a special focus is given to the chemical characterization and bioactivities (namely antioxidant and antimicrobial properties) of several FVB. Lastly, an in-depth review with recent studies (briefly compiled) about the incorporation of fruit and vegetable processing wastes in animal, dairy, beverages, and bakery products, among others is provided.

KEYWORDS
Food by-products; antimicrobial activity; antioxidant proprieties; bioactive compounds; dietary fiber; food products fortification

Introduction

Annually one-third of the food produced worldwide for human consumption, corresponding to approximately 1.3 billion tonnes, is lost or wasted. Quantitatively this represents a cost of around 990 billion dollars, comprising food losses and food processing wastes (FAO 2011; Ferrentino, Asaduzzaman, and Scampicchio 2017). Food processing wastes are frequently defined as residues or by-products derived from processing raw materials to food (Galanakis 2012; Kasapidou, Sossidou, and Mitlianga 2015).

Food by-products have limited commercial exploitation since they are difficult to manage due to their (*i*) high water content (a_w, 0.70–0.95); (*ii*) potential growth of pathogens mainly due to the high a_w; (*iii*) rapid auto-oxidation when they have a high-fat content; and (*iv*) high enzymatic activity that accelerates spoilage (Aljila et al. 2012; Jahurul et al. 2015). On the other hand, the costs of drying, storage, shipment or disposal of by-products are economical and legal limiting factors (Lai et al. 2017).

In Figure 1 it is shown the worldwide percentage of food by-products generated along the upstream processes of the supply chain (FAO 2011). It is highly consensual among the scientific community and recognized world organizations, such as Food and Agriculture Organization of the United Nations (FAO) that fruit and vegetable processing industry is one of the greatest producers of by-products (Gómez and Martinez 2017; FAO 2015). Indeed this industry generates by-products in the form of peels, kernels, pomace, unripe and/or damaged fruits and vegetables (FAO 2015). In Table 1 several examples of industrial waste resulting from the most processed fruits and vegetables worldwide are depicted.

In 2014, Europe generated 100.33 and 73.67 million metric tons of vegetables and fruits, corresponding to 8.6 and 8.9% of global world production, respectively (Statisca 2014a, 2014b). Hence, it is inevitable that food processing industry generates million tons of fruit and vegetable by-products (FVB) per year (Alexandre et al. 2017b).

In order to feed the estimated 9 billion people in 2050, FAO forecasts a 20% increase in food production, so in a near future, it is expected an increasing generation of FVB (FAO 2009; Sharma et al. 2016). Thus, there has been a social, political and environmental pressure to improve profitability and valorization of FVB (Kasapidou, Sossidou, and Mitlianga 2015; Sharma et al. 2016). Additionally, consumers are now more informed and conscious regarding diet-related health problems hence demand the production of "natural" and "eco/green" label food products, which are expected to be safe and health-promoting (Nunes et al. 2016). Bearing these facts in mind and knowing that FVB are sources of several high value-added compounds, these by-products may

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be used as natural food ingredients or as starting material for the preparation of innovative food products (Aljila et al. 2012).

High value-added compounds in fruit and vegetable by-products

As stated, FVB are considerably rich in high-value compounds, such as bioactive compounds and dietary fiber (Duba and Fiori 2015; Ancos et al. 2015; Kowalska et al. 2017). Therefore, in the following sections, a discussion regarding FVB' bioactive compounds, bioactivities (namely antimicrobial and antioxidant properties) and dietary fiber is given.

Bioactive compounds

Bioactive compounds can influence human health due to their biological properties (antioxidant, antimicrobial, anti-inflammatory, anticancer, etc). Generally, their content is lower in the plants' edible organs than their respective by-products (Guil-Guerrero et al. 2016b; Biesalski et al. 2009; del Castillo et al. 2017). These molecules can play a role as an attractant in fruit dispersal and protect the plant from ultra-violet light. Moreover, most bioactive compounds are capable of protecting fruit and vegetables from premature consumption due to their unpleasant tasting, bitterness, and astringency (Padayachee et al. 2017). It should be noted that FVB contains a complex mixture of bioactive compounds, thus physiological activity is typically due to a synergistic action of distinct compounds (Guil-Guerrero et al. 2016b).

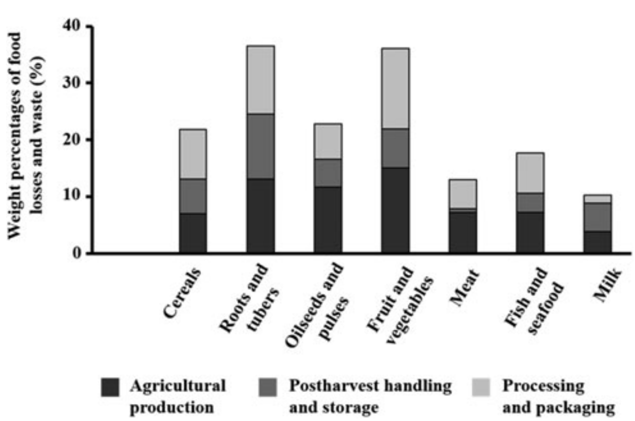

Figure 1. The worldwide percentage of food by-products generated along the upstream processes of the supply chain. Adapted from FAO (2011).

There are two major groups of bioactive compounds: essential and non-essential. The former comprises mostly vitamins and minerals, essential to prevent diseases and to maintain specific biochemical processes in the body. In contrast, non-essential bioactive compounds encompass metabolites such as phenolics, carotenoids, phytosterols, saponins, essential oils, and phytic acids, which allow the maintenance of optimal cellular health, leading to an improvement in longevity (Guil-Guerrero et al. 2016b; Padayachee et al. 2017). Phenolics and carotenoids are the most widely distributed bioactive compounds available in FVB (Padayachee et al. 2017).

Phenolic compounds

Phenolic compounds include a vast array of water-soluble substances (around 8000 different molecules) that are mainly synthesized by the shikimic acid, pentose phosphate and phenylpropanoid pathways. The more structurally complex phenols, i.e. with high-molecular-weight, are often referred to as polyphenols. However, they all have in common at least one aromatic ring with one or more hydroxyl substituent (Singh et al. 2017; del Castillo et al. 2017; Burton-Freeman, Sandhu, and Edirisinghe 2017). The major classes of phenols found in FVB are flavonoids, phenolic acids, and tannins (Babbar and Oberoi 2014).

Flavonoids consist of 15 carbon atoms, arranged in a C6–C3–C6 configuration (Figure 2). Their structure comprises two aromatic rings (A and B), linked through a three-carbon chain (C), usually in the form of a heterocyclic ring (Dua et al. 2016). Different substitution patterns in ring C allow flavonoids to have several subclasses that are present in fruits and/or vegetables, i.e. flavonols, flavones, flavan-3-ols, flavanones, and anthocyanidins. It is thought that flavonoids exert antimicrobial activity due to their capacity to form complexes with both extracellular and soluble proteins as well as bacterial cell walls (Guil-Guerrero et al. 2016a). According to Balasundram et al. (2006) and Rice-Evans et al. (1997) the structural features and nature of substitutions that determine the antioxidant activity of flavonoids are the following: (*i*) number and position of the hydroxyl groups in the A and B rings; (*ii*) existence of a double bond between C2 and C3, conjugated with the 4-keto group in ring C enhances the radical scavenging capacity; (*iii*) occurrence of a double bond between C2 and C3, combined with a 3-hydroxy moiety in ring C, augments the radical scavenging capacity; and (*iv*) substitution of contributing hydroxyl groups by glycosylation decreases the antioxidant activity.

Table 1. Percentage of industrial waste in different fruits and vegetables.

Fruit/vegetable	By-product	Approximate waste (%)	Reference
Apple	Peel, pomace, seed	25	Aljila et al. (2012)
Banana	Peel	35	Aljila et al. (2012)
Citrus	Peel, rag, seed	50	Aljila et al. (2012)
Grape	Stem, skin, seed	20	Aljila et al. (2012)
Mango	Peel, stones	60	Padayachee et al. (2017)
Pomegranate	Peel, mesocarp	40–45	Duarte et al. (2016)
Potato	Peel	15	Aljila et al. (2012)
Tomato	Skin, core, seed	20	Aljila et al. (2012)

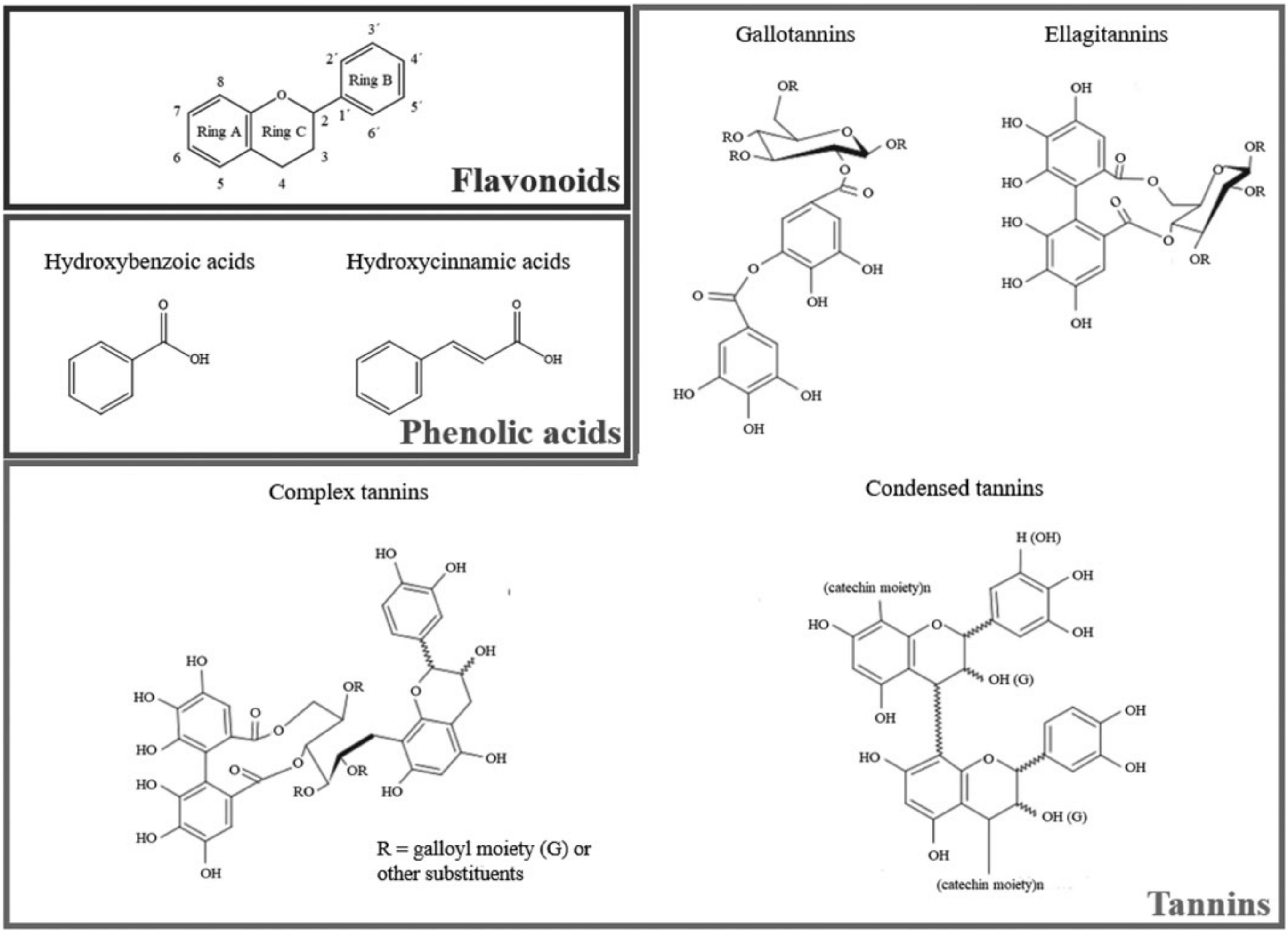

Figure 2. Generic structures of different classes of phenolic compounds (flavonoids, phenolic acids, and tannins). Adapted from Balasundram, Sundram, and Samman (2006); Dua et al. (2016); Sieniawska and Baj (2017).

Phenolic acids (PAs) are formed by a single phenolic ring and an organic carboxylic acid (C_6–C_1 skeleton) and can be subdivided into 2 families: hydroxybenzoic acids (C_6-C_1) and hydroxycinnamic acids (C_6-C_3) (Figure 2). Hydroxycinnamic acids are widely present in food when compared to hydroxybenzoic acids. Sanchez-Maldonado (2014) studied the mode of action of phenolic acids as antimicrobial agents and found that the diffusion of PAs across the membrane leads to cytoplasm acidification and, in some cases, to cell death. Additionally, the antimicrobial potential of hydroxybenzoic acids decreased with an increasing number of hydroxyl groups, while the antimicrobial potential of hydroxycinnamic acids was strongly dependent on the double bond of the side chain (Sanchez-Maldonado 2014). Concerning antioxidant activity of PAs three points should be taken into account: (*i*) it depends on the number and positions of the hydroxyl groups in relation to the carboxyl functional group; (*ii*) it increases with higher degrees of hydroxylation; and (*iii*) hydroxycinnamic acids exhibit higher antioxidant activity when compared to the corresponding hydroxybenzoic acids (Balasundram, Sundram, and Samman 2006).

Tannins are water soluble phenolics with a molar mass between 300 and 3000 Da, with the ability to precipitate proteins. Based on their structural features it is possible to divide this class of compounds into four major groups: gallotannins, ellagitannins, complex tannins and condensed tannins (Figure 2) (Khanbabaee and Ree 2001; Sieniawska and Baj 2017). These molecules function as antioxidants due to the multiple phenolic hydroxyl groups capable of reducing the concentration of free radicals. Also, catechol hydroxyl groups in condensed and complex tannins provide them with the ability to chelate iron and transition metals (Akhtar et al. 2015). Moreover, tannins may act as antimicrobials through the following mechanisms: (*i*) inhibition of enzymatic activity; (*ii*) depletion of metal ions; and (*iii*) precipitation of membrane proteins (Ismail, Sestili, and Akhtar 2012; Akhtar et al. 2015).

By-products derived from grape and pomegranate present the highest total phenolic content in terms of mg Trolox eq./g extract DW, when compared to others FVB depicted in Table 2 ($n = 25$), such as apple peel (Jairath, Chatli, and Biswas 2016), artichoke, cauliflower, date, and persimmon by-products (Ergezer and Serdaroğlu 2018; Costa et al. 2018; Amofa-Diatuo et al. 2017; Jridi et al. 2015; Ramachandraiah and Chin 2018), banana peel (Rebello et al. 2014), mango kernel (Mutua, Imathiu, and Owino 2017), and orange peel (Adiamo et al. 2018). Indeed, the total phenolic content

(TPC) in pomegranate peel and grape pomace ranged between 0.45–168.3 and 16.2–139 mg Trolox eq./g extract DW, respectively (Sandhya et al. 2018; Mashkoor 2014; Tournour et al. 2017; Marchiani et al. 2016b). The source of discrepancies on these concentrations could be related to the fruit/vegetable genetic variety, geographic location, seasonal variation, stage of maturation, and extraction parameters (e.g. nature and concentration of the solvent, solid-liquid ratio, and extraction time and temperature) (Pathak, Mandavgane, and Kulkarni 2017; Ismail, Sestili, and Akhtar 2012; Kharchoufi et al. 2018).

Carotenoids

Carotenoids are lipid soluble pigments localized in the chloroplasts and chromoplasts of fruits and vegetables. Some carotenoids are used as natural pigments in food products (Cooperstone and Schwartz 2016). The backbone of carotenoids is composed of isoprene units and is characterized by a series of conjugated double bonds. To date, over 700 carotenoids have been described. Such high number is due to modifications on the basic structure, such as cyclization, hydrogenation, dehydrogenation, introduction of oxygen functions, migration of double bonds, and chain shortening or elongation (Rodriguez-Amaya 2015). Nevertheless, carotenoids can be categorized as carotenes (hydrocarbons without oxygen) or xanthophylls (hydrocarbons containing oxygen). β-carotene and lycopene (Figure 3), mainly present in carrots and tomatoes, are the most common carotenes, whereas lutein, usually found in dark green leafy vegetables, is one of the most common xanthophylls (Ancos et al. 2015). The conjugated double bond arrangement is primarily responsible for the chemical reactivity of carotenoids with free radicals e.g. lipid peroxyl radicals. Moreover, the antioxidant activity of carotenoids can be related to their effects on the physical properties of lipid bilayer membranes. In this sense, carotenes (non-polar carotenoids) react efficiently only with radicals generated inside the membrane, while xanthophylls, due to their hydroxyl groups, are exposed to an aqueous environment and can also scavenge free radicals generated in the aqueous phase (Widomska 2014).

Various works described in Table 2 analyzed the total or individual carotenoids of grape pomace, lemon peel, olive pomace, persimmon peel, pomegranate pomace, tomato pomace, and guava, orange, and passion fruit by-products (Andrés et al. 2017a; Bellur Nagarajaiah and Prakash 2015; Casarotti et al. 2018; Tekgül and Baysal 2018; Hwang 2011). According to Andrés et al. (2017b), tomato pomace displayed a relatively high concentration of total carotenoids (1325.0 μg lycopene eq./g extract DW) when compared to pomegranate pomace (122.9), olive pomace (18.7), and grape pomace (7.0). In another study, Casarotti et al. (2018) examined the main individual carotenoids of by-products derived from guava, orange, and passion fruit. The values of the sum of β-carotene and lycopene content were the highest in the latter by-product (84.3 μg/g extract DW), whereas guava by-products presented the lowest concentration of these pigments (12.7) (Casarotti et al. 2018).

Bioactivities

Antioxidant properties. Antioxidants are defined as snthetic or natural compounds capable of inhibiting or delaying oxidation, reducing the concentration of transition metal ions and/or free radicals (Alexandre et al. 2017a). Transition metals, such as iron and copper ions are catalytic metals with the ability to initiate oxidation of O_2 and other biomolecules, therefore producing free radicals (Allen 2015).

Free radicals (atoms, molecules, or ions) are the main species on which antioxidants act upon. Chemically they possess one or more unpaired electrons in an atomic orbital. Many free radicals are highly reactive and can either donate or accept an electron from other molecules. Therefore, they attack lipids, nucleic acids, and proteins in biological systems causing cell damage (Babbar and Oberoi 2014). Also, these molecules have been associated with more than 100 pathologies such as cardiovascular diseases, cancer, diabetes and degenerative age-associated processes (Hassan et al. 2017). Free radicals belong to two families: reactive oxygen species (ROS) (e.g. hydroxyl radical, superoxide anion radical, hydrogen peroxide, oxygen singlet) and reactive nitrogen species (RNS) (e.g. peroxynitrite) (Babbar and Oberoi 2014). The human organism has three lines of defense against ROS and RNS. The first one includes enzymes (superoxide dismutase, catalase, glutathione peroxidase, glutathione reductase and peroxiredoxins) and non-enzymatic compounds (ceruloplasmin, ferritin, transferrin and albumin) capable of neutralizing free radicals. The second line of defense is composed by non-enzymatic antioxidants such as certain vitamins (ascorbic acid, α-tocopherol) and carotenoids that rapidly inactivate radicals. The last line consists of enzymatic repair mechanisms against damage caused by free radicals (Mirończuk-Chodakowska, Witkowska, and Zujko 2018). In the food industry, antioxidants are used to preserve food flavor and color by preventing oxidation of food constituents (Lai et al. 2017). However, they can also be added to foodstuff to balance the rates of production and release of free radicals in the body, thus working as exogenous antioxidants (Mirończuk-Chodakowska, Witkowska, and Zujko 2018).

Table 2 presents the antioxidant activity of several FVB. Taking in account the inhibition concentration of 50% of initial 2,2-Diphenyl-1-picrylhydrazyl (DPPH) concentration (IC_{50}), grape pomace (0.013 mg/mL) alongside pomegranate peel (0.017 mg/mL) displayed the lowest IC_{50} values and thus the highest antioxidant potential (Demirkol and Tarakci 2018; Pal et al. 2017). Other extracts from olive pomace, plantain peel, and persimmon peel needed a concentration of 0.02, 0.055, and 0.24 mg/mL to inhibit half of the DPPH radical (Andrés et al. 2017a; Choe, Kim, and Kim 2017; Arun et al. 2015). The presence of phenolic compounds in food processing by-products is frequently linked to their antioxidant capacity (Kaderides, Goula, and Adamopoulos 2015). Therefore, it is not surprising that by-products derived from grape and pomegranate exhibited by far the highest antioxidant values.

Regarding ferric reducing antioxidant power (FRAP) assay, by-products derived from grape and pomegranate

Table 2. Analysis of the high value-added compounds (total phenolic content, total carotenoids content, and total dietary fiber) and antioxidant activity (assessed by ABTS, DPPH, and FRAP methods) of fruit and vegetable by-products.

By-product	High value-added compounds			Antioxidant activity assays			Reference
	TPC (mg gallic acid eq./g extract DW)	TCC (µg lycopene eq./g extract DW)	TDF (g/100 g extract DW)	ABTS (mg Trolox eq./g extract DW)	DPPH (mg Trolox eq./g extract DW)	FRAP (mg Trolox eq./g extract DW)	
Apple peel	17.2	—	—	82.2[i]	—	—	Jairath et al. (2016)
Apple pomace	—	—	75.8	—	—	—	Rochelle et al. (2016)
Apricot pomace	—	—	72.3	—	—	—	Ayar et al. (2018)
Artichoke bracts	0.044	—	—	—	71.42[i]	—	Ergezer and Serdaroğlu (2018)
Artichokes by-products	20.4	—	—	16.8	—	74.3[m]	Costa et al. (2018)
Banana peel	29.2	—	—	242.2[j]	—	14.0[j]	Rebello et al. (2014)
	4.95	—	—	—	9.23	0.32	Hernández-Carranza et al. (2016)
Beetroot pomace	3.70	—	—	5.08	—	6.88	Hidalgo et al. (2018)
Blackcurrant pomace	203.5[c]	—	—	—	—	—	Tańska et al. (2016)
Carrot pomace	—	54.56[e]	44.8	—	—	—	Bellur Nagarajaiah and Prakash (2015)
Cauliflower leaves	0.24	—	—	—	—	—	Amofa-Diatuo et al. (2017)
Cauliflower stems	0.40	—	—	—	—	—	Amofa-Diatuo et al. (2017)
Date by-products	4.42	—	—	—	—	—	Jridi et al. (2015)
Elderberry pomace	138.6[c]	—	—	—	—	—	Tańska et al. (2016)
Grape juice by-product	23.36	—	—	—	—	—	Vital et al. (2018)
Grape must lees	—	—	67.2	—	—	—	Ayar et al. (2018)
Grape pomace	32.2[a]	7.0	29.4	—	0.05[k]	—	Andrés et al. (2017b)
	139	—	—	—	280	—	Tournour et al. (2017)
	60	—	—	—	123	100	Jana et al. (2018)
	99.0	—	—	118.7	—	487[m]	Costa et al. (2018)
	34.96	—	—	—	0.013[k]	—	Demirkol and Tarakci (2018)
	16.06	—	—	—	—	—	Marchiani et al. (2016a)
	28.3	—	54.5	—	89.31[l]	24.79	Šporin et al. (2018)
Grape press oil cake	65	—	—	—	138	113	Jana et al. (2018)
Grape seed	74	—	—	—	190	145	Jana et al. (2018)
Guava by-products	2.53	7.91[g] + 4.77[h]	89.8	—	4.35	—	Casarotti et al. (2018)
Hazelnut skin	0.20	—	56.8	—	1.01[j]	—	Bertolino et al. (2015)
Lemon peel	29.2	—	—	—	238.6	80.13	Nishad et al. (2018)
	—	2.4[f]	—	—	—	—	Tekgül and Baysal (2018)
Mango kernel	72.1	—	3.2	—	92.2[i]	—	Mutua et al.2017
Mango kernel (defatted)	—	—	3.7	—	—	—	Shabeer et al. (2016)
Olive pomace	85.4[a]	18.6	7.0	—	0.02[k]	—	Andrés et al. (2017a)
Orange by-product	4.21	39.14[g] + 18.51[h]	58.2		2.84	—	Casarotti et al. (2018)
Orange peel	25.9	—	—	—	—	—	Adiamo et al. (2018)

(*continued*)

Table 2. Continued.

By-product	High value-added compounds			Antioxidant activity assays			Reference
	TPC (mg gallic acid eq./g extract DW)	TCC (µg lycopene eq./g extract DW)	TDF (g/100 g extract DW)	ABTS (mg Trolox eq./g extract DW)	DPPH (mg Trolox eq./g extract DW)	FRAP (mg Trolox eq./g extract DW)	
	—	—	—	28.04	8.84	—	Ding et al. (2016)
Orange pulp	11.4	—	—	—	—	—	Adiamo et al. (2018)
Passion fruit by-products	3.84	56.07[g] + 28.57[h]	64.2		3.35	—	Casarotti et al. (2018)
Persimmon calyx	46.3	—	—	—	85[i]	—	Ramachandraiah and Chin (2018)
Persimmon peel	59.6	—	—	—	60[i]	—	Ramachandraiah and Chin (2018)
	12.4	—	—	—	0.24[k]	—	Choe et al. (2017)
	18.3	3740[f]	21.8	—	—	7.2[j]	Hwang (2011)
Persimmon seed	41.3	—	—	—	75[i]	—	Ramachandraiah and Chin (2018)
Plantain peel	15.21[d]	—	64.3		0.055[k]	—	Arun et al. (2015)
Pomegranate peel	139.4	—	—	0.59[k]	0.017[k]	—	Pal et al. (2017)
	—	—	—	221.5	—	—	Marchi et al. (2015)
	420.6[b]	—	—	—	—	—	Basiri et al. (2015)
	0.45	—	—	92.1[i]	97.1[i]	—	Sandhya et al. (2018)
	168.3	—	—	—	—	142.2	Mashkoor (2014)
	—	—	16.7	—	—	—	Ismail et al. (2016)
Pomegranate pomace	134.8[a]	122.9	43.5	—	0.16[k]	—	Andrés et al. (2017b)
Potato peel	—	—	29.7	—	—	—	Jeddou et al. (2017)
Rosehip pomace	186.2[c]	—	—	—	—	—	Tańska et al. (2016)
Rowanberry pomace	167.4[c]	—	—	—	—	—	Tańska et al. (2016)
Tomato peel	5.30	—	—	4.2	—	6.48[m]	Costa et al. (2018)
Tomato pomace	13.8[a]	1325.0	46.5	—	0.94[k]	—	Andrés et al. (2017b)

[a]mg gallic acid eq./g liquid extract;
[b]mg tannic acid eq./g extract DW;
[c]mg catechin eq./g extract DW;
[d]mg quercetin eq./g extract DW;
[e]µg standard not specified eq./g extract DW;
[f]µg β-carotene eq./g extract DW;
[g]µg β-carotene/g extract DW;
[h]µg lycopene/g extract DW;
[i]Percentage (%) of ABTS or DPPH radical inhibition;
[j]mM trolox eq./g extract DW;
[k]IC_{50}, concentration (mg/mL) at 50% scavenging of ABTS or DPPH radical;
[l]mg gallic acid eq./g extract DW;
[m]mg $FeSO_4.7H_2O$ eq./g extract DW.

ABTS 2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) diammonium salt, *DPPH* diphenyl-1-picrylhydrazyl, *DW* dry weight, *FRAP* ferric reducing antioxidant power, *TPC* total phenolics content, *TCC* total carotenoids content, *TDF* total dietary fiber.

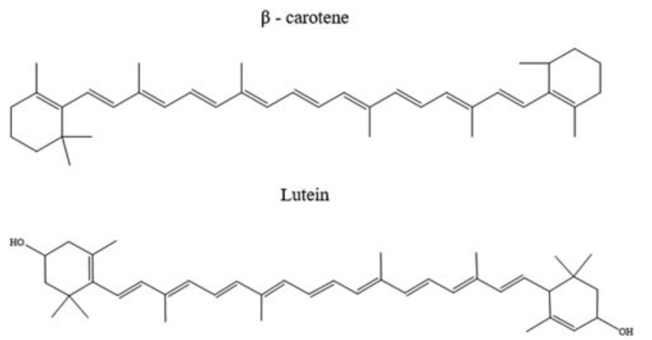

Figure 3. Chemical structure of β-carotene and lutein. Adapted from Guil-Guerrero et al. (2016b).

(Jana et al. 2018; Mashkoor 2014) showed, once again, better antioxidant activity than others FVB such as banana peel (Hernández-Carranza et al. 2016), beetroot pomace (Hidalgo et al. 2018), and lemon peel (Nishad et al. 2018). For 2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) diammonium salt (ABTS) radical cation decolorization assay, pomegranate peel and grape pomace displayed a scavenging capacity of 221.5 and 118.7 mg Trolox eq./g extract dry weight (DW) (Marchi et al. 2015; Costa et al. 2018), respectively, whereas for orange peel, artichoke by-products, beetroot pomace, and tomato peel the ABTS values were 28.0, 16.8, 5.1, and 4.2 mg Trolox eq./g extract DW, correspondingly (Costa et al. 2018; Hidalgo et al. 2018; Ding et al. 2016).

Antimicrobial activity. Antimicrobial agents from synthetic or natural sources are known to promote death or growth inhibition of pathogenic and spoilage microorganisms. Microbial activity is one of the main problems in the food industry and apart from the loss of product's quality, the outbreak of foodborne illnesses is always a concern among all intervening parties in the supply chain (Khorshidian et al. 2018). Indeed, it is estimated that 600 million people in the world contract foodborne illness every year due to the ingestion of contaminated food, of which 420 000 pass away (WHO 2017).

One of the most important foodborne diseases is human listeriosis caused by the bacteria *Listeria monocytogenes*. The number of listeriosis cases in the European Union has been increasing. In fact, in 2005 there were 1439 confirmed cases, compared to 2530 cases in 2016. This poses a serious threat since 95% of the cases results in hospitalization and 20 to 30% in death (Datta and Burall 2018; Chlebicz and Śliżewska 2018). As summarized in Table 3 numerous FVB derived from apple (Agourram et al. 2013), cauliflower (Maria Sanz-Puig et al. 2016), elderberry (Coman et al. 2018), grape (Moreira et al. 2016), citrus (Ramadan et al. 2015), and pomegranate (Wu et al. 2018) have proved their antimicrobial effectiveness against *L. monocytogenes*. Another potential foodborne pathogen is *Staphylococcus aureus*. Indeed, a meta-analysis conducted by Paudyal et al. (2018) revealed that *S. aureus* was the fourth most common pathogen in Chinese foods. This Gram-positive bacteria causes foodborne infections varying from mild infections of skin to post-operative wound infections (Rubab et al. 2018). Several FVB can act as antimicrobial agents upon *S. aureus*, such as by-products generated from artichoke (Zhu et al. 2005), banana (Mordi et al. 2016), elderberry (Radványi et al. 2013), grape (Xu et al. 2014), mango (Mutua, Imathiu, and Owino 2017; Arbos, Stevani, and Castanha 2013), orange (Casquete et al. 2015), pomegranate (Agourram et al. 2013; Rochelle et al. 2016), and tomato (Gaafar, Asker, and Bagato 2015). The antimicrobial activity does not confine only to the above-mention microorganisms. Others, FVB demonstrated antimicrobial activity against a wide range of bacteria involved in foodborne diseases and food spoilage processes, such as *Vibrio parahaemolyticus* (Sirajudin et al. 2014), *Salmonella* spp. (Jain 2011), *Salmonella enterica* (Wafa et al. 2017), *Bacillus subtilis* (Mohammadsadeghi et al. 2013), *Bacillus cereus* (Issa, Talib, and Habash 2016), *Escherichia coli* (Sanhueza et al. 2017; Jakubcova et al. 2015), *Pseudomonas aeruginosa* (Poveda et al. 2018), *Pseudomonas fluorescens* (Agourram et al. 2013), *Enterococcus faecalis* (Shabani and Sayadi 2014), and *Staphylococcus xylosus* (Alexandre et al. 2019).

Dietary fiber

Fruit and vegetable by-products are also an important source of dietary fiber (DF), commonly known as non-starch polysaccharides. These polysaccharides reach the colon almost intact since the human upper digestive tract does not have the proper enzymes to break them down (Ferrentino, Asaduzzaman, and Scampicchio 2017; Padayachee et al. 2017). Dietary fiber can be classified in two groups such as water-soluble (e.g. pectin) and water-insoluble (e.g. cellulose and lignin). Soluble fiber has the following main beneficial physiological functions: (*i*) increases the viscosity of food digesta, changing the rate of nutrient release and absorption in gastrointestinal tract; and (*ii*) lowers blood cholesterol concentration since it binds to bile salts in small intestine leading to an excess fecal excretion of bile salts. In order to compensate such loss, the organism uses blood cholesterol to synthesize new bile salts. In contrast, insoluble dietary fiber has less physiological effects in the upper gastrointestinal tract and is fermented in less extent by the colonic microflora. Nonetheless, insoluble DF plays an important role in intestinal regulation through mechanical peristalsis (Ancos et al. 2015; Padayachee et al. 2017). Both DF groups have also important functional properties as food additives, e.g. flavor binding, water-holding capacity, swelling capacity, increasing viscosity, and gel formation, that can be crucial when formulating certain food products (Alexandre et al. 2017c; Ferrentino, Asaduzzaman, and Scampicchio 2017). Also, DF can interfere with the bioavailability of bioactive compounds since polyphenols and carotenoids are usually associated with non-starch polysaccharides. Hence, during the upper intestine digestion of DF-rich foods, a minor portion of bioactive compounds pass to the blood system, whereas the remaining part reaches the colon and is fermented by the gut microbiota (Radenkovs et al. 2018; Palafox-Carlos, Ayala-Zavala, and González-Aguilar 2011).

Table 3. Effect of fruit and vegetable by-products upon microorganisms involved in foodborne illness and food spoilage.

By-product	*P. fluorescens*	*P. aeruginosa*	*E. coli*	*S. aureus*	*L. monocytogenes*	*B. cereus*	*L. lactis*	*S. xylosus*	*L. sakei*	*S. enterica*	*V. parahaemolyticus*	*M. luteus*	*S. sonnei*	*Salmonella* spp.	*E. faecalis*	*B. subtilis*	*L. innocua*	*C. sporogenes*	*C. difficile*	*A. lwoffi*	*A. junii*	*A. pittii*	*Pseudomonas* spp.	*P. vulgaris*	*A. baumannii*	*Klebsiella* spp	*C. sakazakii*	Reference
Apple peel	✓	✓	✓	✓	✓	✓	✓		✓	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	Agourram et al. (2013)
Apple pomace	–	×	×	×	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	Rochelle et al. (2016)
Artichoke leafs	–	✓	✓	✓	–	–	–	–	–	✓	–	✓	–	–	–	✓	–	–	–	–	–	–	–	–	–	–	–	Zhu et al. (2005)
Artichoke stem	–	×	✓	✓	–	–	–	–	–	×	–	×	–	–	–	✓	–	–	–	–	–	–	–	–	–	–	–	Zhu et al. (2005)
Banana peel	–	–	✓	✓	–	–	–	–	–	–	–	–	–	×	–	–	–	–	–	–	–	–	–	–	–	–	–	Mordi et al. (2016)
	–	–	–	✓	–	–	–	–	–	–	✓	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	Sirajudin et al. (2014)
	–	✓	–	✓	–	–	–	–	–	–	–	–	–	✓	–	–	–	–	–	–	–	–	–	–	–	–	–	Jain (2011)
Cauliflower residue	–	–	✓	–	✓	✓	–	–	–	✓	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	Sanz-Puig et al. (2015)
Elderberry peel	–	–	✓	✓	✓	✓	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	Coman et al. (2018)
Elderberry pomace	–	–	×	✓	–	–	–	–	–	–	–	–	–	–	✓	–	–	–	–	–	–	–	–	–	–	–	–	Radványi et al. (2013)
	–	✓	✓	✓	–	–	–	–	–	✓	–	–	–	–	–	✓	–	–	–	–	–	–	–	–	–	–	–	Mohammadsadeghi et al. (2013)
Grape pomace	–	–	✓	✓	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	Sanhueza et al. (2017)
	–	–	–	✓	–	–	–	–	–	–	–	–	✓	–	–	–	–	–	–	–	–	–	–	–	–	–	–	Xu et al. (2014)
	–	✓	✓	✓	✓	–	–	–	–	–	–	–	–	✓	–	–	–	–	–	–	–	–	–	–	–	–	–	Moreira et al. (2016)
Grape seeds	–	✓	✓	✓		–	–	–	–	✓	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	Poveda et al. (2018)
Grape stems	–	✓	×	✓	✓	–	–	–	–	–	–	–	–	–	✓	–	–	–	–	–	–	–	–	–	–	–	–	Gouvinhas et al. (2018)
Guava peel	–	–	✓	✓	–	✓	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	Issa et al. (2016)
Guava pomace	–	×	×	×	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	Rochelle et al. (2016)
Lemon peel	✓	–	✓	✓	✓	–	–	–	–	✓	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	Ramadan et al. (2015)
	–	–	×	✓	a	–	–	–	–	✓	–	–	–	–	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	Casquete et al. (2015)
	–	–	✓	–	–	–	–	–	–	✓	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	Sanz-Puig et al. (2016)
Mango kernel	–	–	✓	✓	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	Mutua et al. (2017)
	–	✓	✓	✓	–	–	–	–	–	✓	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	Arbos et al. (2013)
	–	✓	–	✓	–	–	–	–	–	–	–	–	–	–	✓	–	–	–	–	–	–	–	–	–	–	–	–	Shabani and Sayadi (2014)
Mango peel	–	✓	✓	✓	–	–	–	–	–	✓	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	Arbos et al. (2013)
Orange peel	✓	–	✓	✓	✓	–	–	–	–	✓	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	Ramadan et al. (2015)

(*continued*)

Table 3. Continued.

By-product	*P. fluorescens*	*P. aeruginosa*	*E. coli*	*S. aureus*	*L. monocytogenes*	*B. cereus*	*L. lactis*	*S. xylosus*	*L. sakei*	*S. enterica*	*V. parahaemolyticus*	*M. luteus*	*S. sonnei*	*Salmonella* spp.	*E. faecalis*	*B. subtilis*	*L. innocua*	*C. sporogenes*	*C. difficile*	*A. lwoffi*	*A. junii*	*A. pittii*	*Pseudomonas* spp.	*P. vulgaris*	*A. baumannii*	*Klebsiella* spp	*C. sakazakii*	Reference
	–	–	✓	✓	[a]	–	–	–	–	✓	–	–	–	–	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	✓	Casquete et al. (2015)
	–	–	✓	–	–	–	–	–	–	✓	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	Sanz-Puig et al. (2016)
Orange pomace	–	×	×	×	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	Rochelle et al. (2016)
Pomegranate peel	✓	✓	✓	✓	✓	✓	✓	✓	×	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	Agourram et al. (2013)
	–	–	–	–	–	–	–	–	–	✓	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	Wafa et al. (2017)
	–	–	–	–	✓	–	–	–	–	–	✓	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	Wu et al. (2018)
	–	✓	✓	✓	✓	✓	–	✓	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	Alexandre et al. (2019)
	–	✓	✓	✓	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	Rochelle et al. (2016)
Pomegranate pomace	✓	×	✓	✓	×	×	×	×	×	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	Agourram et al. (2013)
Rosehip pressing	–	–	✓	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	Jakubcova et al. (2015)
Tomato pomace	–	×	×	×	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	Rochelle et al. (2016)
	–	✓	✓	✓	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	Gaafar et al. (2015)

[a]Displayed antimicrobial activity although only on specific strains.

A considerable number of FVB hold on their composition more than 50 g of DF per 100 g of extract DW (Table 2). Some examples include apple pomace (Ayar et al. 2018), apricot pomace (Ayar et al. 2018), grape must lees (Ayar et al. 2018), grape pomace (Šporin et al. 2018), hazelnut skin (Bertolino et al. 2015), plantain peel (Arun et al. 2015), and orange and passion fruit by-products (Casarotti et al. 2018). Conversely, carrot, grape, and tomato pomaces, as well as pomegranate and potato peels, display a concentration of DF between 10 and 50 g/extract DW (Bellur Nagarajaiah and Prakash 2015; Andrés et al. 2017a; Ismail et al. 2016; Jeddou et al. 2017). Lastly, mango kernel and olive pomace were reported to have a DF content of 3.2–3.7 and 7.0 g/extract DW, respectively (Shabeer et al. 2016; Mutua, Imathiu, and Owino 2017; Andrés et al. 2017a).

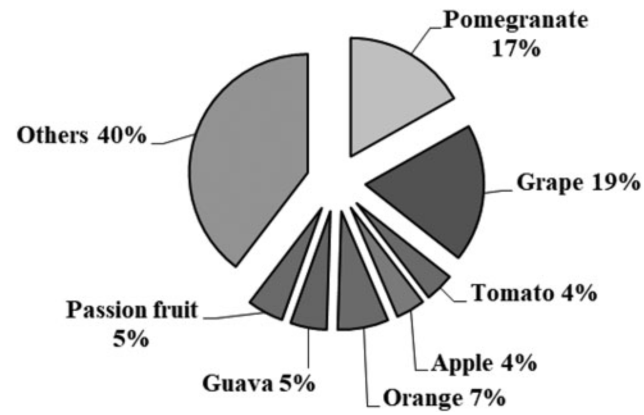

Figure 4. Source of the most used fruit and vegetable by-products to fortified food products (n = 101). These data were obtained using the compilation of articles related to the application of fruit and vegetable by-products in animal products, beverages, dairy products, bakery products, and other food products.

Application of fruit and vegetable by-products in food products

As previously discussed, pomegranate peel and grape pomace presented a relatively high antioxidant potential and TPC when compared to others FVB. These features could explain why both food processing by-products are frequently selected to fortify animal products, beverages, dairy products, bakery products, among others (Figure 4).

The quality and safety of a food product can be significantly improved through the addition of FVB, however when selecting the best concentration, one should take into account the sensory alterations (e.g. regarding color, odor taste, texture, mouth-feel, and overall acceptability descriptors) entailed by the fortification. Thereby, one must choose the formulation which improve or at least hold the sensory qualities of the original product. Thus, alongside the review related to the changes in bioactive compounds, dietary fiber, bioactivities and other prominence parameters after incorporating FVB in food products, an analysis concerning sensory changes is provided hereinafter.

Animal products

According to Shah et al. (2014), in 2008, the meat, poultry, and fish commodity lost around 8.7 and 60.0 billion dollars at retail and consumer levels, respectively, in the United States of America alone. One of the reasons for such losses could be related to the high susceptibility of animal products to oxidation and microbial spoilage since they present a significant content in water, lipids, and proteins (Shah, Bosco, and Mir 2014; Mattos et al. 2017). Consequently, this leads to shorter shelf lives and undesirable sensorial changes (e.g. texture, flavor, color, odor, aftertaste) throughout storage (Ahmad et al. 2015). Despite the degree of deterioration could be reduced by adding artificial antioxidants such as butylated hydroxyanisole (BHA) and butylated hydroxytoluene (BHT) their use is restricted due to possible toxic effects (Franco, Carballo, and Lorenzo Rodriguez 2016). Therefore, the demand for natural and cost-effective antioxidants such as those derived from FVB has been increasing as evidenced by the number of recent works (since 2015) summarized in Table 4.

Overall, FVB proved to be efficient in delaying lipid and/or protein oxidation of meat (Kryževičūtė et al. 2017; Turgut, Soyer, and Işıkçı 2016; Turgut, Işıkçı, and Soyer 2017; Ergezer and Serdaroğlu 2018; Saleh et al. 2017; Habib et al. 2018; Nishad et al. 2018; Andrés et al. 2017a; Ramachandraiah and Chin 2018; Choe, Kim, and Kim 2017; Klinjapo, Areerat, and Sutthirak 2017; Bobko et al. 2017; Lee et al. 2015), poultry (Biswas et al. 2015), and fish (Pal et al. 2017; Berizi, Shekarforoush, and Hosseinzadeh 2016; Basiri et al. 2015), when compared to the control without any added antioxidant. Turgut et al. (2016) incorporated a freeze-dried pomegranate peel extract in beef meatballs (1000 mg/100 g). After 8 days of storage at 4 °C, the per cent reduction of thiobarbituric acid reactive substances (TBARS), an indicator of secondary lipid oxidation products, was 53 and 50% in 1% extract and positive control (BHT) samples, respectively, as compared to control. Concerning protein oxidation, at the end of storage, total carbonyl content (TCC) in 1% extract and BHT beef meatballs decreased about 26% for both samples, in comparison to control. Moreover, extract-fortified meatballs displayed, over storage, the lowest per cent reduction in free thiol content (FTC), suggesting a lower extent of protein oxidation reactions in this group (Turgut, Soyer, and Işıkçı 2016). In another study, grounded pork meat was fortified with a persimmon peel extract (Choe, Kim, and Kim 2017). After 12 days of storage at 3 °C, the content of primary lipid oxidation products determined by measuring the peroxide values (PV) and conjugated dienes (CD) was lower in extract- (200 mg/100 g) and BHT-supplemented meats. The PV percentage reduction was 43 and 34%, respectively, when compared to the grounded pork without antioxidant, whereas the extract group was the most effective at delaying CD generation. Furthermore, for TCC, the persimmon peel extract and BHT samples had per cent inhibition values of 54 and 48%, respectively, at the end of the storage period, compared to control samples. A similar trend was obtained for FTC since extract and BHT supplementation reduced disulfide bonds formation to 19 and 24%, correspondingly. Given these

Table 4. Recent works (since 2015) regarding the application of fruit and vegetable by-products in animal products.

Product modified	By-product	Type/ Storage conditions	Best dosage[a]	Key findings: High value-added compounds	Key findings: Bioactivities and others	Key findings: Sensorial evaluation	Reference
Beef meatballs	Raspberry pomace	Extract/26 days at 4 °C	1000 mg/100 g	—	↓ Lipid oxidation (TBARS) ↓ Microbial growth	↑ Homogeneity, intensity of color ↓ discoloration	Kryževičūtė et al. (2017)
	Pomegranate peel	Extract/8 days at 4 °C	500–1000 mg/100 g	—	↓ Lipid and protein oxidation (TBARS, PV, FTC, PCC)	↓ Rancid odor, color changes	Turgut et al. (2016)
	Pomegranate peel	Extract/6 months at −18 °C	1000 mg/100 g	—	↓ Lipid and protein oxidation (TBARS, PV, FTC, PCC)	= Rancid odor, OA	Turgut et al. (2017)
Beef patties	Artichoke bracts	Extract/7 days at 2 °C	27 mg/100 g	↑ TPC	↓ Lipid and protein oxidation (PV, CD, TBARS, P-Av, PCC) ↑ DPPH	—	Ergezer and Serdaroğlu (2018)
Beef sausages	Pomegranate peel	Powder/2 months at −18 °C	2500–5000 mg/100 g	—	↓ Lipid and protein oxidation (TBARS, TVB-N) ↓ Microbial growth	—	Saleh et al. (2017)
Carabeef nuggets	Pomegranate peel	Powder/14 days at 4 °C	4000 mg/100 g	↑ TPC	↓ Lipid oxidation (TBARS, FFA) ↑ DPPH	= Appearance, flavor, texture, OA	Habib et al. (2018)
Chicken meat	Grape pomace	Extract/7 months at −23 °C	12 mg/100 g	↑ TPC	↑ ORAC, ICA	—	Tournour et al. (2017)
Goat meatballs	Lemon peel	Extract/6 months at −18 °C	1000 mg/100 g	—	↓ Lipid and protein oxidation (PV, TBARS, PCC, FTC)	↑ Colour, taste, odor, OA	Nishad et al. (2018)
Lamb meat	Tomato pomace	Extract/7 days at 2 °C	0.3 mL of extract spread on lamb meat surface	—	= Lipid and protein oxidation (TBARS, FTC) = Microbial growth	—	Andrés et al. (2017b)
Lamb patties	Grape pomace	Extract/7 days at 2 °C	100 mg/100 g	—	↓ Lipid and protein oxidation (TBARS, FTC) ↓	—	Andrés et al. (2017a)

(*continued*)

Table 4. Continued.

Product modified	By-product	Type/ Storage conditions	Best dosage[a]	Key findings: High value-added compounds	Key findings: Bioactivities and others	Key findings: Sensorial evaluation	Reference
					Microbial growth		
	Olive pomace	Extract/7 days at 2 °C	100 mg/100 g	—	↓ Lipid and protein oxidation (TBARS, FTC) ↓ Microbial growth	—	Andrés et al. (2017a)
	Pomegranate pomace	Extract/7 days at 2 °C	100 mg/100 g	—	= Lipid and protein oxidation (TBARS, FTC) ↓ Microbial growth	—	Andrés et al. (2017a)
	Tomato pomace	Extract/7 days at 2 °C	100 mg/100 g	—	= Lipid and protein oxidation (TBARS, FTC) ↓ Microbial growth	—	Andrés et al. (2017a)
	Olive wet cake	Extract/9 days at 4 °C	58–115 mg/100 g	—	↓ Lipid and protein oxidation (TBARS, PCC) ↑ FRAP; = ORAC Extension of shelf-life in 3 days	= OA	Muíño et al. (2017)
Mackerel (grounded)	Pomegranate peel	Extract/8 days at 4 °C	200 mg/100 g	—	↓ Lipid and protein oxidation (TBARS, PV)	—	Pal et al. (2017)
Porcine patties	Persimmon seed/ peel/calyx	Powder/14 days at 4 °C	500 mg/100 g	—	↓ Lipid and protein oxidation (TBARS, PV)	—	Ramachandraiah and Chin (2018)
Pork meat (grounded)	Persimmon peel	Extract/12 days 3 °C	200 mg/100 g	—	↓ Lipid and protein oxidation (TBARS, CD, PV, FTC, PCC)	—	Choe et al. (2017)
Pork meatballs	Mango peel	Extract/10 days at 4 °C	0.2 mL/100 g	↑ TPC	↓ Lipid oxidation (TBARS)	↓ Rancid odor	Klinjapo et al. (2017)
Pork sausages	Grape seed	Extract/12 days at 4 °C	1 mL/100 g	—	↓ Lipid oxidation (TBARS)	= Appearance, texture, aroma, taste	Bobko et al. (2017)
	Onion peel	Extract/28 days at 4 °C	50 mg/100 g	—	↓ Lipid and protein oxidation		Lee et al. (2015)

(*continued*)

Table 4. Continued.

				Key findings			
Product modified	By-product	Type/ Storage conditions	Best dosage[a]	High value-added compounds	Bioactivities and others	Sensorial evaluation	Reference
					(TBARS, TVB) = Microbial growth	= Colour, flavor, tenderness, OA; ↑ off-flavor	
Poultry meat wafers	Apple peel	Powder/2 months at 37 °C	2000 mg/100 g	↑ TPC, TFC, gallic acid and β-carotene content	↓ Lipid oxidation (TBARS, PV, FFA) ↑ ABTS, DPPH, SASA	↑ Colour, appearance, flavor, texture, after taste, OA; = meat flavor	Biswas et al. (2015)
	Banana peel	Powder/2 months at 37 °C	2500 mg/100 g	↑ TPC, TFC, gallic acid and β-carotene content	↓ Lipid oxidation (TBARS, PV, FFA) ↑ ABTS, DPPH, SASA	↑ Colour, appearance, flavor, texture, after taste, OA; = meat flavor	Biswas et al. (2015)
Shrimp	Pomegranate peel	Extract/10 days at 4 °C	Sample dipped in 1000–2000 mg/100 mL	—	↓ Lipid and protein oxidation (TBARS, TVB-N) ↓ Microbial growth	↑ Colour, appearance, odor, texture, color after cooking	Basiri et al. (2015)
		Extract/10 days at 4 and 12 °C	Sample dipped in 500 mg/100 mL	—	↓ Microbial growth	—	Wu et al. (2016)
Trout	Pomegranate peel	Extract/6 months at −18 °C	Sample dipped in water with 4% (wt/vol) extract		↓ Microbial growth ↓ Lipid and protein oxidation (TBARS, PV, TVB-N)	↑ Texture; = odor, appearance; ↓ color, OA	Berizi et al. (2016)
Tuna	Pomegranate peel	Extract/10 days at 4 and 12 °C	170 mg/100 mL	—	↓ Microbial growth	—	Wu et al. (2016)

aWithout overall significant differences or less pronounced differences when compared to the highest concentrations.
CD conjugate dienes, *FFA* free fatty acids, *FTC* free thiol content, *ICA* iron(II) chelating ability, OA overall acceptability, *P-Av* P-para-Anisidine value, *PCC* protein carbonyl content, *PV* peroxide values, *SASA* superoxide anion radical scavenging activity, *TBARS* thiobarbituric acid reactive substances, *TFC* total flavonoids content, *TMA* trimethylamine, *TPC* total phenolic content, *TVB* total volatile basic, *TVB-N* total volatile basic nitrogen.

outcomes the extract could be a potential substitute for artificial antioxidants (Choe, Kim, and Kim 2017). The delaying of lipid/protein oxidation in FVB-fortified animal products has been related to the antioxidant potential of phenolic compounds (Ergezer and Serdaroğlu 2018; Habib et al. 2018; Muíño et al. 2017; Klinjapo, Areerat, and Sutthirak 2017; Biswas et al. 2015). For instance, Ergezer and Serdaroğlu, (2018) studied the impact of adding BHT and an extract derived from artichoke by-products to beef patties. During storage, the incorporation of the extract (27 mg/100 g) inhibited lipid and protein oxidation largely than BHT treatment. The authors attributed such findings to the TPC and antioxidant potential of artichoke by-products since, by the end of storage, this samples displayed a 42 and 114% increase in TPC and scavenging activity against the DPPH radical, respectively, in comparison to control, whereas for BHT samples these values stood at 4 and 9%.

Several works also evaluated the antimicrobial potential of FVB in different animal matrixes (Kryževičūtė et al. 2017; Saleh et al. 2017; Andrés et al. 2017a, 2017b; Lee et al. 2015; Wu et al. 2016; Basiri et al. 2015; Berizi, Shekarforoush, and Hosseinzadeh 2016). Andrés et al. (2017b) added grape, olive, tomato, and pomegranate pomaces extract to lamb patties. After 7 days at refrigerated storage, all FVB-fortified meats showed less 10 to 21% of microbial counts for mesophilic microorganisms than the group without additives. Moreover, none of the extracts affected lactic acid bacteria counts and only pomegranate and tomato pomaces reduced psychrophiles (decrease of 15–17%) and *Enterobacteriaceae* (decrease of 26–41%) populations. Consistent microbiological results were also found for beef sausages supplemented with pomegranate peel and shrimp dipped in a solution containing this by-product (Basiri et al. 2015; Saleh et al. 2017). Further studies which selected pomegranate's by-products corroborated these later findings (Wu et al. 2016; Berizi, Shekarforoush, and Hosseinzadeh 2016). On the other hand, no antimicrobial effect was noticed when tomato pomace and onion peel extracts were added to lamb meat and pork sausages, respectively (Andrés et al. 2017a; Lee et al. 2015).

Despite most FVB prevent oxidation and function as antimicrobials agents in animal food products, they can modify sensory descriptors (Karre, Lopez, and Getty 2013). Therefore, sensorial evaluations should be conducted alongside physicochemical and/or microbiological assays (Kryževičūtė et al. 2017; Turgut, Işıkçı, and Soyer 2017; Ergezer and Serdaroğlu 2018; Habib et al. 2018; Nishad et al. 2018; Muíño et al. 2017; Klinjapo, Areerat, and Sutthirak 2017; Bobko et al. 2017; Lee et al. 2015; Biswas et al. 2015; Berizi, Shekarforoush, and Hosseinzadeh 2016). Sensory scores for color, odor, taste and overall acceptability in meatballs supplemented with citrus peel extract (100 mg/100 g) improved through storage in comparison to control samples (Nishad et al. 2018). In another investigation, apple and banana peels were added to poultry meat wafer (2000 mg/100 g and 2500 mg/100 g, respectively). During storage at ambient temperature, several sensory descriptors such as color, flavor, texture, aftertaste, meat flavor intensity, and overall acceptability were enhanced, apart from meat flavor intensity which was similar to control (Biswas et al. 2015). Other studies reported an improvement in color (Kryževičūtė et al. 2017; Turgut, Soyer, and Işıkçı 2016), texture (Berizi, Shekarforoush, and Hosseinzadeh 2016; Basiri et al. 2015), and hindrance of rancid odor formation (Turgut, Soyer, and Işıkçı 2016; Klinjapo, Areerat, and Sutthirak 2017), while several works stated that FVB did not affect any of the evaluated sensory descriptors (Turgut, Işıkçı, and Soyer 2017; Habib et al. 2018; Muíño et al. 2017; Bobko et al. 2017; Lee et al. 2015).

Dairy products

High-fat content dairy foods, such as cheese and butter are highly susceptible to lipid oxidation due to several factors (e.g. milk constituents, light exposure, and fermentation) (Iriondo-DeHond, Miguel, and del Castillo 2018). Hence, to retard oxidation processes, the addition of bioactive compounds from FVB to dairy matrixes has been studied as shown in Table 5. Mahajan et al. (2015) dipped a buffalo cheese in a solution containing pomegranate peel extract (2000 mg/100 mL). After 28 days of storage at 4 °C, the per cent reduction of TBARS' value was 15%, whereas free fatty acid content, which is often related to the growth of lipolytic microorganisms, decreased 24% as compared to control. The authors also evaluated the microbial growth and found that extract-treated samples had about 16, 25, and 29% lower counts for total microorganisms, psychrophilic, and yeasts and molds, respectively, when compared to the non-fortified cheese. In another study, butter was enriched with an extract from tomato peel and seeds. Throughout storage, fortified butter (40 mg/100 g) had the lowest PV, possibly due to the large content of lycopene and phenolics in the extract (Abid et al. 2017).

Phenolic compounds are present in considerable amounts in ruminant milk, however, processes such as thermal treatments or bacterial degradation could decrease phenolic content in dairy products (O'Connell and Fox 2001). Therefore, numerous studies tried to improve phenolic content and/or antioxidant activity (Costa et al. 2018; Marchiani et al. 2016a, 2016b; Sandhya et al. 2018; Santos et al. 2017; Aliakbarian et al. 2015; Vital et al. 2018; Jridi et al. 2015; Demirkol and Tarakci 2018; Bertolino et al. 2015). For instance, when powdered skin hazelnuts were directly included in yoghurt, DPPH radical scavenging capacity and TPC of the supplemented yoghurts (3000 mg/100 g) increased, on average, 96 and 31%, respectively, in comparison to control. Moreover, total dietary fiber (TDF) increased from undetectable levels in control samples to about 9.5 g/100 g in fortified yoghurts (Bertolino et al. 2015). In a different work, Vital et al. (2018) added increasing doses of powdered grape juice by-product to ice cream (2500–10,000 mg/100 g) and the TPC improved 4.6- and 11.7-times, respectively. For a similar dosage, a lower increase in TPC (1.6-times) was reported when grape pomace extract was included in goat milk prior to fermentation (Santos et al. 2017). This may be due to the form of the by-product

Table 5. Recent works (since 2015) regarding application of fruit and vegetable by-products in dairy products.

Product modified	By-product	Type/ Storage conditions	Best dosage(s)[a]	Key findings: High value-added compounds	Key findings: Bioactivities and others	Key findings: Sensorial evaluation	Reference
Butter	Tomato peel and seeds	Extract/2 months at 4 °C	40 mg/100 g	—	↓ Lipid oxidation (PV, K_{232}, K_{270}) = Viability of lactic acid bacteria	—	Abid et al. (2017)
Cheese	Pomegranate peel	Extract/28 days at 4 °C	Sample dipped in 2000 mg/ 100 mL solution	—	↓ Lipid oxidation (TBARS, FFA) ↓ Microbial growth	↑ Flavour, texture, OA; = appearance, sourness	Mahajan et al. (2015)
	Grape pomace	Powder/-	5000–10,000 mg/100 g	↑ TPC, TFC	↑ ABTS, FRAP	↑ Astringency, fibrous, friability, acidity, adhesiveness; ↓ hardness, odor, sweetness; = aroma, saltiness	Costa et al. (2018)
	Tomato peels	Powder/-	5000–10,000 mg/100 g	↑ TPC, TFC	↑ ABTS, FRAP	↑ Hardness, odor, aroma, acidity, saltiness, astringency, friability, fibrous, adhesiveness, humidity; = sweetness	Costa et al. (2018)
	Artichoke and broccoli by-products	Powder/-	5000–10,000 mg/100 g	↑ TPC, TFC	↑ ABTS, FRAP	↑ Hardness, odor, aroma, acidity, saltiness, astringency, friability, fibrous, adhesiveness, humidity, sweetness	Costa et al. (2018)
	Grape pomace	Powder/30 days at 28 °C	1600 mg/100 g	↑ TPC	↑ DPPH = Growth of starter and nonstarter cultures	—	Marchiani et al. (2016a)
	Grape pomace	Powder/120 days at 28 °C	1600 mg/100 g	↑ TPC	↑ DPPH = Growth of starter and nonstarter cultures	—	Marchiani et al. (2016a)
Curd	Pomegranate peel	Extract/15 days at 5 °C	1000 mg/100 mL	↑ TPC	↑ ABTS, DPPH ↓ Microbial growth	↑ Flavour, texture, OA; ↓ color	Sandhya et al. (2018)
Fermented milk	Grape pomace	Extract/28 days at 4 °C	2000 mg/100 g fermentation broth	↑ TPC	= Growth of starter and probiotic bacteria	↑ Flavour, color, consistency, OA	Santos et al. (2017)
	Olive pomace	Extract/50 days at 4 °C	n.s.	↑ TPC	↑ ABTS, DPPH = Growth of starter bacteria	—	Aliakbarian et al. (2015)
	Grape pomace	Extract/50 days at 4 °C	n.s.	↑ TPC	↑ ABTS, DPPH = Growth of starter bacteria	—	Aliakbarian et al. (2015)
	Guava/Orange/Passion fruit by-products	Extract/28 days at 4 °C	1000 mg/100 mL	—	= Growth of probiotic bacteria	—	Casarotti et al. (2018)
Ice cream	Grape juice by-product	Powder/40 days at −18 °C	2500–10,000 mg/100 g	↑ TPC	↑ DPPH	No control was used as standard	Vital et al. (2018)
Milk-based dessert	Date by-products	Syrup and powder/-	16,000 mg/100 g	↑ TPC	↑ DPPH, FRAP	No control was used as standard	Jridi et al. (2015)

(*continued*)

Table 5. Continued.

Product modified	By-product	Type/ Storage conditions	Best dosage(s)[a]	Key findings: High value-added compounds	Key findings: Bioactivities and others	Key findings: Sensorial evaluation	Reference
	Grape must lees	n.s./2 months at −20 °C	1000–4000 mg/100 g	—	↑ Survival rates of probiotic bacterium ↑ Microbial growth	↓ Flavour, texture, OA; = appearance, mouthfeel	Ayar et al. (2018)
	Apricot pomace	n.s./2 months at −20 °C	500–2000 mg/100 g	—	↑ Survival rates of probiotic bacterium ↑ Microbial growth	↓ Flavour, texture, OA; = appearance, mouthfeel	Ayar et al. (2018)
	Apple pomace	n.s./2 months at −20 °C	500–3000 mg/100 g	—	↑ Survival rates of probiotic bacterium ↑ Microbial growth	↓ Flavour, texture, OA; = appearance, mouthfeel	Ayar et al. (2018)
Yoghurt	Grape pomace	Powder/21 days at 4 °C	1000–5000 mg/ 100 g milk	↑ TPC	↑ DPPH = Viability of the starter culture	—	Demirkol and Tarakci (2018)
	Grape peel	Powder/21 days at 4 °C	6000 mg/ 100 g yoghurt	↑ TPC, gallic acid, protocatechuic acid, catechin, epicatechin, rutin, quercetin	↑ DPPH = Viability of the starter culture	↓ Appearance, odor, taste, flavor, texture, OA	Marchiani et al. (2016b)
	Hazelnut skin	Powder/21 days at 4 °C	3000 mg/ 100 g yoghurt	↑ TPC, gallic acid, protocatechuic acid, procyanidin B1, gallocatechingallate, 3-coumaric acid, rutin ↑ TDF	↑ DPPH = Viability of the starter culture	= Odour, texture, taste, flavor, OA	Bertolino et al. (2015)
	Orange peel	Extract/21 days at 4 °C	600 mg/100 g milk	—	↑ Growth of starter culture during fermentation	↑ Cohesiveness, adhesiveness, taste, whey exudation; ↓ aftertaste	Arioui et al. (2017)
	Pineapple peel	Powder/ 28 days at 4 °C	1000 mg/100 mL milk	↑ TDF	↓ Fermentation time	—	Sah et al. (2016)
	Pineapple peel	Powder/ 28 days at 4 °C	1000 mg/100 mL milk	—	↑ Growth of starter and probiotic cultures	—	Sah et al. (2015)

[a]Without overall significant differences or less pronounced differences when compared to the highest concentrations.

ABTS 2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) diammonium salt, *DPPH* diphenyl-1-picrylhydrazyl, *FFA* free fatty acids, *FRAP* ferric reducing antioxidant power, n.s. not specified, *OA* overall acceptability, *PV* peroxide value, *TBARS* thiobarbituric acid reactive substances, *TFC* total flavonoid content, *TPC* total phenolic content.

(extract and powder) and/or grape differences, as seasonal differences, maturation phase, and geographic area. Regarding the viability of the probiotic and starter microorganisms, fortified samples did not inhibit their growth or survival during or after fermentation (Santos et al. 2017). Indeed, one major concern related to FVB-fortified dairy products is the interference of bioactive compounds with the survival rates of nonstarter, starter and other microorganisms involved in fermentation processes. Similar outputs for the effect of FVB upon probiotic bacteria were described by Casarotti et al. (2018), which enriched fermented goat milk with extracts from guava, orange, and passion fruit by-products, Aliakbarian et al. (2015), who incorporated grape and olive pomace in a fermentation medium to produce fermented milk, among other authors (Bertolino et al., 2015; Marchiani et al. 2016a, 2016b; Abid et al., 2017; Demirkol and Tarakci, 2018). Conversely, the presence of pineapple peel powder in yoghurts enhanced probiotic growth during storage at 4 °C (Sah et al., 2015).

The addition of FVB can lead to either positive or undesirable effects on the sensory parameters of the final product, depending on the (*i*) dosage; (*ii*) form of the by-product (usually powder or extract); and (*iii*) dairy matrix in which it is incorporated. In cheese supplemented with powdered FVB (grape pomace, tomato peels, artichoke, and broccoli by-products) an increase in astringency and acidity attributes was obtained (Costa et al. 2018). Pomegranate peel extract used in curd (1000 mg/100 mL) significantly improved flavor, texture, and overall acceptability after 15 days of storage, when compared to control (Sandhya et al. 2018). Moreover, in a yoghurt matrix fortified with orange peel extract (600 mg/100 g milk), the cohesiveness, adhesiveness, and taste descriptors had better scores relatively to control samples, whereas aftertaste was negatively affected (Arioui, Ait Saada, and Cheriguene 2017).

Beverages

Fruit beverages are a practical way of consuming significant amounts of bioactive compounds. Indeed, about 36 billion liters of fruit juice and fruit nectar were consumed worldwide in 2016 (Statisca 2017c). Therefore, these food products can work as carriers to deliver health benefiting components derived from FVB (Carrillo et al. 2014). In Table 6 there are depicted several recent studies which added FVB to different beverages.

Most studies demonstrated an improvement in TPC and/or antioxidant activity after incorporating pomegranate (Altunkaya et al. 2013; Tárrega et al. 2014), orange (Adiamo et al. 2018), banana (Ortiz et al. 2017a), grape (Jana et al. 2018), and tamarind (Natukunda, Muyonga, and Mukisa 2016) by-products in beverages. For instance, fortified fresh orange juice with a banana peel extract (500 mg/100 mL) and reported an increase of about 21 and 150% for DPPH and FRAP assays, respectively, compared to the non-fortified juice (Ortiz et al. 2017a). Altunkaya et al. (2013) incorporated a pomegranate peel extract in apple juice (500 mg/100 mL) and the relative free radical concentration decreased 5%, while TPC increased 19%, when compared to the control. Conversely, Jana et al. (2018) added an extract of grape press oil cake to grape juice (50 mg/100 mL) and described an improvement of about 70, 140, 190, 50, and 160% for TPC, FRAP, DPPH, and catechin and epicatechin content, correspondingly, relatively to non-fortified juices. The authors selected the same extract to fortified apple juice and obtained similar results for the above-mention methods (Jana et al. 2018). As concluded in Section 2.1.1, by-products derived from grape and pomegranate display similar TPC values. In this sense, it was expected a less marked improvement in TPC for the last study, or higher values for this method in the former work since it used an extract concentration ten times higher.

Regarding sensory tests, Amofa-Diatuo et al. (2017) enriched apple juice with an extract from cauliflower stem by-product (10 mL/100 mL). Despite appearance was similar to control, the remaining sensory descriptors (smell, flavor, texture, aftertaste, and overall acceptability) were evaluated with lower scores (Amofa-Diatuo et al. 2017). In another investigation, when pomegranate peel extract was included in dealcoholized wine (160 mg/100 mL), it resulted in a product with more intense yeast odor and flavor, acidity, and astringency. By contrast, berry and apple flavor intensity diminished, whereas wine and berry flavor scores were statistically identical to control (Tárrega et al. 2014). Natukunda et al. (2016) also reported changes in several sensorial parameters. After supplementing mango juice with powered tamarind seed (1500 mg/100 mL), appearance, color, flavor, taste, consistency, mouth-feel, sweetness, and overall acceptability scores were lower than the control juice (Natukunda, Muyonga, and Mukisa 2016). Among the works presented in Table 6, this latter study reported the highest dosage of by-product. If the authors opted for an extract from tamarind seed, the bioactive compounds would be more concentrated and smaller dosages would be required to achieve similar results for TPC and better sensory scores. Other works found no differences between fortified and non-fortified juices for overall acceptability (Altunkaya et al. 2013; Jana et al. 2018), while banana peel extract improved flavor in orange juices (Ortiz et al. 2017a, 2017b).

Bakery products

Bakery products are widely consumed all around the world (Statisca 2017b). The total volume of consumption encompassed in the bread and bakery European sector was about 30 000 million kilograms in 2017 (Statisca 2017a). Furthermore, it is forecast that the revenue from this industry will grow annually by 2.3% until 2021 (Statisca 2017b). Typically, the main ingredient of bakery products is white wheat flour. Despite being a good source of energy and nutrients it displays low antioxidant activity since most bioactive compounds are located in the bran and aleurone layer (Dziki et al. 2014). Therefore, there are numerous studies regarding the addition of FVB-based ingredients to bread, cakes, cookies, biscuits, and muffins as shown in Table 7.

Table 6. Recent works (since 2013) regarding the application of fruit and vegetable by-products in beverages.

Product modified	By-product(s)	Type/Storage conditions	Best dosage(s)[a]	Key findings: High value-added compounds	Key findings: Bioactivities and others	Key findings: Sensorial evaluation	Reference
Apple juice	Pomegranate peel	Extract/-	500 mg/100 mL	↑ TPC	↑ Reduction of Fremy's salt radical; = ABTS	= Colour, odor, sweetness, acidity, flavor, OA	Altunkaya et al. (2013)
	Grape press oil cake	Extract/-	50 mg/100 mL	↑ TPC, catechin and epicatechin content	↑ ABTS, FRAP	= OA	Jana et al. (2018)
	Cauliflower stem	Extract/-	10 mL/100 mL	= TPC	= FRAP	= Appearance; ↓ smell, flavor, texture, aftertaste, OA	Amofa-Diatuo et al. (2017)
Carrot juice	Orange pulp	Extract/-	154 mg/100 mL	↑ TPC	↑ DPPH	—	Adiamo et al. (2018)
	Orange peel	Extract/-	154 mg/100 mL	↑ TPC	↑ DPPH	—	Adiamo et al. (2018)
Dealcoholized wine	Pomegranate peel	Extract/-	160 mg/100 mL	↑ TPC	—	↑ Acidity, astringency, yeast odor and flavor; ↓ berry and apple flavor; = wine and berry odor	Tárrega et al. (2014)
Grape juice	Grape press oil cake	Extract/-	50 mg/100 mL	↑ TPC, catechin and epicatechin content	↑ ABTS, FRAP	= OA	Jana et al. (2018)
Mango juice	Tamarind seed	Powder/-	1500 mg/100 mL	↑ TPC, TFC, TCT	↑ DPPH	↓ Appearance, color, flavor, taste, consistency, mouth-feel, sweetness, OA; = thickness	Natukunda et al. (2016)
Oat-fermented beverage	Guava/Orange/Passion fruit by-products	Extract/28 days at 4 °C	1000 mg/100 mL	—	= Growth of probiotic bacteria	—	Casarotti et al. (2018)
Orange juice	Banana peel	Extract/-	500 mg/100 mL	—	↑ ABTS, FRAP = Lipid oxidation (β-carotene bleaching)	↑ Flavour; = color	Ortiz et al. (2017a)
	Banana peel	Extract/30 days at 5 °C	380 mg/100 mL	—	= ABTS, DPPH = Lipid oxidation (β-carotene bleaching)	↑ Colour, flavor, herbaceous notes	Ortiz et al. (2017b)
	Banana peel	Extract/45 days at 5 °C	380 mg/100 mL	—	= ABTS, DPPH = Lipid oxidation (β-carotene bleaching)	↑ Appearance, herbaceous notes, body and complexity; ↓ acidity	Ortiz et al. (2017b)
Rice-fermented beverage	Guava/Orange/Passion fruit by-products	Extract/28 days at 4 °C	1000 mg/100 mL	—	= Growth of probiotic bacteria	—	Casarotti et al. (2018)

[a]Without overall significant differences or less pronounced differences when compared to the highest concentrations.

ABTS 2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) diammonium salt, *DPPH* diphenyl-1-picrylhydrazyl, *FRAP* ferric reducing antioxidant power, n.s. not specified, *OA* overall acceptability, *TCT* total condensed tannins, *TFC* total flavonoid content, *TPC* total phenolic content.

Maner et al. (2017) replaced a portion of white wheat flour with grape pomace powder at dosages of 5, 10, 15, and 20 g/100 g. Adding lower powder levels (5 g/100 g) resulted in the best organoleptic scores in cookies and significantly increased TPC, total flavonoids, tannins, and anthocyanins contents in 2.3, 2.0, 1.3, and 12.5-fold, respectively, when compared to control cookies. Besides, antioxidant activity measured by FRAP assay was improved by 2.5-times. Pathak et al. (2016) incorporated mango peel powder at increasing levels (1, 3 and 5 g/100 g) in wheat bread to enhance its bioactivities. Three grams per 100 g of flour was considered the best concentration. At this dosage, TPC increased from 220 to 507 mg gallic acid eq./100 g as well as DPPH inhibition (from 22 to 50%) and FRAP values (from 159 to 1124 μM $FeSO_4.7H_2O$/100 g). Thus, it is stated that if proper amounts of mango peel powder were chosen, it could function as a potential health-promoting ingredient (Pathak et al. 2016). Several other FVBs such as such as pomegranate by-products (Ismail et al. 2016; Bhol, Lanka, and Bosco 2016), plantain peel (Arun et al. 2015), beetroot pomace (Hidalgo et al. 2018), grape pomace (Šporin et al. 2018), apple pomace (Mir et al. 2017), rosehip, rowanberry, blackcurrant, and elderberry pomaces (Tańska et al. 2016), guava seeds and pomace (Khalifa et al. 2016), and raspberry and cranberry pomaces (Mildner-Szkudlarz et al. 2016) had proven their effectiveness to enhance phenolic compounds content and antioxidant activity in bakery products. Furthermore, a variety of studies incorporated carotenoids-rich FVB in cookies (Bellur Nagarajaiah and Prakash 2015), bread (Kampuse et al. 2015), and cakes (Ordóñez-Santos, Martínez-Girón, and Figueroa-Molano 2016). For example, Kampuse et al. (2015) reported a 13-fold increase in total carotenoids after supplemented wheat bread with pumpkin pomace powder (5.5 g/100 g dough). Interestingly, when fresh pumpkin pomace was used, a dosage of 27.7 g/100 g dough was required to obtain similar results and, as expected, this extremely high concentration impaired various sensory attributes.

Dietary fiber from FVB can be introduced in bakery products formulation in order to (*i*) reduce calorie content, (*ii*) improve antioxidant activity since it is frequently in association with significant amounts phenolics compounds and carotenoids, and (*iii*) enhance the beneficial physiological functions related to soluble dietary fiber since bakery food products display a lower content of this fiber fraction (Quiles et al. 2018). Mir et al. (2017) investigated the partial replacement of brown rice flour in crackers with powders made of two varieties of apple pomace, in the following concentrations: 0, 3, 6, and 9 g/100 g. Samples enriched with 9% of powder were superior in several nutritional aspects, especially regarding TFD content. Indeed, soluble fiber content increased about 12.3- to 17.3-times, whereas insoluble fiber concentration was improved 1.6-times when compared to control crackers (Mir et al. 2017). Toledo et al. (2017) also reported identical improvements in the insoluble fiber content of cookies fortified with powdered melon peels (15 g/100 g). Bender et al. (2017) studied the effect of increasing doses (5 to 10 g/100 g) of powdered grape pomace skins wheat flour replacement in muffins. As expected, for the lowest and highest dosages, TDF increased, on average, 40 and 69%, respectively (Bender et al. 2017). Other studies found similar outputs after incorporating FVB in bakery products formulation (Shabeer et al. 2016; Bellur Nagarajaiah and Prakash 2015; Tańska et al. 2016; Conti-Silva and Ferreira Roncari 2015; Bhol, Lanka, and Bosco 2016; Oliveira et al. 2016; Khalifa et al. 2016; Jeddou et al. 2017).

The form of the by-product can have a direct impact upon the physicochemical, microbial, and sensorial parameters. For instance, Ismail et al. (2016) supplemented pomegranate peel extract and powdered pomegranate peel to wheat flour cookies at 0.25–1.0 g/100 g and 1.5–7.5 g/100 g, respectively. Total dietary fiber content increased significantly after replacing wheat flour with the grounded peel, however the same did not happen with peel extract (Ismail et al. 2016). This could explain why most of studies use grounded and powdered by-products instead of extracts to improve TDF content. Conversely, all extract concentrations displayed higher values for TPC and antioxidant potential (FRAP and DPPH assays) when compared to the highest dosage of powdered peel. Throughout storage, a similar trend was followed by the microbiological evolution since total plate counts were, on average, 45% lower in cookies fortified with peel extract. These authors also performed organoleptic tests (taste, color, crispness, texture, and overall acceptability). Although both treatments exhibited, over storage, sensory scores above the threshold level, the cookies supplemented with pomegranate peel extract were superior in every descriptor and presented fairly compatible scores with control samples (Ismail et al. 2016). Comparable results were reported by Jeddou et al. (2017) after added potato peel powder to a cake formulation. In this case, the sensory parameters evaluated were crumb color, odor, taste, tenderness, aspect, and overall acceptability. Despite no significant differences were detected between the tested concentrations (2 - 10 g/100 g) and the control cakes, it was clear that increasing replacing doses impaired most sensory attributes (Jeddou et al. 2017). Indeed, it has been demonstrated that concentrations above 10% could significantly diminish the organoleptic quality of the final product (Bhol, Lanka, and Bosco 2016; Shabeer et al. 2016; Tańska et al. 2016; Oliveira et al. 2016). However, as stated in the Section 3.2., the selected food matrix to incorporate the FVB can play an important role in determining the sensorial quality of FVB-supplemented bakery products. For instance, for a high dose fortification (above 10%), Toledo et al. (2017) described identical scores for appearance, aroma, texture, and overall acceptability between cookies supplemented with powders from pineapple and apple by-products and cookies without additives.

Other food products

The application of FVB does not only confine to the abovemention food groups. In fact, as evidenced in Table 8, several works enriched candies (Kumar et al. 2018; Cappa, Lavelli, and Mariotti 2015), fruit purees (Bobinaite et al.

Table 7. Recent works (since 2015) regarding the application of fruit and vegetable by-products in bakery products.

				Key findings			
Product modified	By-product	Type/Storage conditions	Best dosage(s)[a]	High value-added compounds	Bioactivities and others	Sensorial evaluation	Reference
Cookies	Grape pomace	Powder/-	5–10 g/100 g flour	↑ TPC, TFC, TTC, TAC	↑ FRAP	↑ Texture, mouth sensation, color, aroma, OA; = appearance, taste	Maner et al. (2017)
	Pineapple central axis	Powder/-	15 g/100 g flour	↑ TDF	—	↑ Taste; = appearance, aroma, texture, OA	Toledo et al. (2017)
	Apple endocarp	Powder/-	15 g/100 g flour	↑ TDF	—	↑ Taste; = appearance, aroma, texture, OA	Toledo et al. (2017)
	Melon peels	Powder/-	15 g/100 g flour	↑ TDF	—	↓ Taste, texture, OA; = appearance, aroma, OA	Toledo et al. (2017)
	Pomegranate peel	Extract/3 months	0.3–1.0 g/100 g flour	↑ TPC = TDF	↑ FRAP, DPPH ↓ Microbial growth ↓ Lipid oxidation (TBARS, FFA)	↓ Taste, color, crispness, texture, OA	Ismail et al. (2016)
	Pomegranate peel	Powder/3 months	1.5–7.5 g/100 g flour	↑ TPC ↑ TDF	↑ FRAP, DPPH ↓ Microbial growth ↓ Lipid oxidation (TBARS)	↓ Taste, color, crispness, texture, OA	Ismail et al. (2016)
	Defatted mango kernel	Powder/-	15–20 g/100 g flour	↑ TDF	—	↓ Colour, flavor, texture, aroma, crispness, OA	Shabeer et al. (2016)
	Plantain peel	Powder/-	10 g/100 g flour	↑ TPC ↑ TDF	↑ DPPH	= Colour, taste, texture, OA	Arun et al. (2015)
	Carrot pomace	Powder/2 months	8 g/100 g flour	↑ Total carotenoids, β-carotene ↑ TDF	= Lipid oxidation (PV, FFA)	= Appearance, color, texture, aroma, OA	Bellur Nagarajaiah and Prakash (2015)
Biscuits	Beetroot pomace	Extract/-	5.7–14.9 g/100 g	↑ TPC	↑ FRAP, ABTS	—	Hidalgo et al. (2018)
	Apple pomace	Powder/-	9 g/100 g flour	↑ TPC, TFC ↑ TDF	↑ DPPH, reducing power	↑ Flavour; = OA; ↓ appearance, color, texture;	Mir et al. (2017)
	Grape leaves	Extract/2 months	1 g/100 g dough	—	↓ Lipid oxidation (PV)	= Colour, surface character, crumb color, texture, taste, mouth feel	Hefnawy et al. (2016)
Biscuits	Rowanberry pomace	Powder/-	20 g/100 g flour	↑ TDF	↑ DPPH	= Colour, shape, hardness; ↓ taste, aroma, sweetness, crispness	Tańska et al. (2016)
	Blackcurrant pomace	Powder/-	20 g/100 g flour	↑ TDF	↑ DPPH	= Colour, shape, hardness, crispness; ↓ taste, aroma, sweetness	Tańska et al. (2016)
	Elderberry pomace	Powder/-	20 g/100 g flour	↑ TDF	↑ DPPH	= Colour, shape, crispness, hardness, aroma, sweetness; ↓ taste	Tańska et al. (2016)
Bread	Passion fruit peel	Powder/-	20 g/100 g flour	↑ TDF	—	↑ Difference intensity; = appearance,	Conti-Silva and Ferreira Roncari (2015)

(*continued*)

Table 7. Continued.

Product modified	By-product	Type/Storage conditions	Best dosage(s)[a]	Key findings: High value-added compounds	Key findings: Bioactivities and others	Key findings: Sensorial evaluation	Reference
						aroma, texture, flavor, OA	
	Mango peel	Powder/-	3 g/100 g flour	↑ TPC	↑ FRAP, DPPH	↑ Fruity aroma, fruity taste, after taste, crumb color, hardness, stickiness; ↓ bread aroma	Pathak et al. (2016)
	Pomegranate bagasse	Powder/-	15 g/100 g flour	↑ TPC ↑ TDF	↑ DPPH	↑ Flavour; ↓ appearance, texture, color, taste, mouth feel, OA	Bhol et al. (2016)
	Pumpkin pomace	Powder/-	5.5 g/100 dough	↑ Total carotenoids	—	= Appearance, crust, crumb elasticity, porosity, taste and aroma	Kampuse et al. (2015)
	Grape pomace	Powder/-	6 g/100 g flour	↑ TPC	↑ DPPH, FRAP	↑ Odour (crumb, sour, and sweet), taste (sweet, sour, bitter), flavor intensity, aftertaste, off taste; = salty taste, yeast flavor	Šporin et al. (2018)
Cakes	Peach palm peel	Powder/-	2.5–7.5 g/100 g	↑ Total carotenoids	—	↑ Colour, taste, odor, OA; ↓ texture	Ordóñez-Santos et al. (2016)
	Orange peel	Powder/-	12.5 g/100 g flour	↑ TDF		= Appearance, color, odor; ↓ flavor, texture	Oliveira et al. (2016)
	Passion fruit peel	Powder/-	20 g/100 g flour	↑ TDF		= Appearance, color; ↓ odor, flavor, texture	Oliveira et al. (2016)
	Guava seeds	Powder/8 days at 25 °C	5–10 g/100 g	↑ TPC ↑ TDF	↑ DPPH ↓ Lipid oxidation (TBARS)	—	Khalifa et al. (2016)
Cakes	Guava pomace	Powder/8 days at 25 °C	5–10 g/100 g	↑ TPC ↑ TDF	↑ DPPH ↓ Lipid oxidation (TBARS)	—	Khalifa et al. (2016)
	Potato peel	Powder/-	5 g/100 g flour	↑ TDF	—	= Crumb color, odor, taste, tenderness, aspect, OA	Jeddou et al. (2017)
Muffins	Raspberry pomace	Powder/-	10–20 g/100 g flour	↑ Anthocyanin, flavonols, ellagic acid	—	—	Mildner-Szkudlarz et al. (2016)
	Cranberry pomace	Powder/-	10–20 g/100 g flour	↑ Anthocyanin, flavonols	—	—	Mildner-Szkudlarz et al. (2016)
	Grape peel	Extract/-	5–10 g/100 g flour	↑ TDF	—	= Colour, flavor, taste, texture, OA	Bender et al. (2017)

[a]Without overall significant differences or less pronounced differences when compared to the highest concentrations.
OA overall acceptability, *TPC* total phenolic content, *TFC* total flavonoids content, *TTC* total tannins content, *TAC* total anthocyanins content.

2016), mustard (Davis et al. 2018), and pasta (Pasqualone et al. 2017) with bioactive compounds from FVB.

Bobinaite et al. (2016) enriched two types of fruit purees with freeze-dried raspberry pomace extract (1200 mg/100 g). For each puree, the extract addition increased TPC in 1.8 and 2.3-times, whereas antioxidant activity, assessed by the DPPH method, was enhanced 3.2 and 1.9-times, respectively, when compared to unfortified samples. Similar improvements were obtained for total anthocyanin content and free ellagic acid contents. Despite no differences were noticed in color, odor, and texture sensory attributes, a lower score for taste was recorded due the increase bitterness and astringency. The authors attributed such outcome to the ellagitannin content, which increased about 3.0-times in both fortified purees (Bobinaite et al. 2016). Indeed, when tannins are consumed they bind to salivary proteins and produce a taste which humans identify as astringency (Crozier, Jaganath, and Clifford 2007).

In another study, Cappa et al. (2015) investigated the effect of adding grape peel powders with different particle sizes on a fruit candy (6.3 g/100 g). Generally, all powders increased the anthocyanin, flavonol and procyanidin contents of the candies, resulting in higher FRAP values. Pasqualone et al. (2017) also obtained a 64 and 49% enhancement in TPC and antioxidant capacity (ABTS assay), respectively, after incorporating an extract from artichoke bracts in fresh pasta dough. Comparable results for both methods were reported by Davis et al. (2018), which supplement mustard, a condiment with low content in bioactive compounds, with powdered berry pomaces from blueberry and cranberry. Furthermore, TDF content significantly increased in all tested dosages (5–25 g/100 g). For the highest concentration, TDF improvement ranged between 38 and 40%. Nonetheless, sensory scores related to appearance, color, aroma, flavor, texture, and overall acceptability were lower in pomace-fortified mustards. To overcome this problem the authors suggest a reduction in the particle size of the powder as well as more research regarding mustard formulation (Davis et al. 2018).

Final remarks

By-products derived from fruit and vegetable sources displayed significant amounts of high value-added compounds, such as phenolics and carotenoids, which in turn are responsible for the antioxidant capacity and antimicrobial activity against bacteria involved in foodborne diseases and food spoilage processes. Pomegranate and grape by-products stand out from other food processing residues since they present higher levels of phenolics and antioxidant capacity. Indeed, these features could justify why both by-products are frequently selected to be incorporated in food products.

Overall, supplementing foodstuff with FVB improved bioactive compounds and dietary fiber contents. Furthermore, a delay in oxidation processes and microbial growth was noticed, especially in animal products. Regarding sensory analysis of FVB-fortified products, the results greatly depend

Table 8. Recent works (since 2015) regarding the application of fruit and vegetable by-products in miscellaneous food products.

Product modified	By-product	Type/Storage conditions	Best dosage(s)[a]	Key findings: High value-added compounds	Key findings: Bioactivities and others	Key findings: Sensorial evaluation	Reference
Candies	Beetroot pomace	Extract/-	9.2 g/100 g	↑ TPC	↑ DPPH	↑ OA	Kumar et al. (2018)
	Grape peel	Powder/-	6.3 g/100 g	↑ Anthocyanin, flavonol, procyanidin	↑ FRAP	—	Cappa et al. (2015)
Fruit purees	Raspberry pomace	Extract/-	1.2 g/100 g	↑ TPC, TAC, free ellagic acid, ellagitannins	↑ DPPH	= Colour, odor, texture; ↓ Taste	Bobinaite et al. (2016)
	Raspberry pomace	Extract/-	1.2 g/100 g	↑ TPC, TAC, free ellagic acid, ellagitannins	↑ DPPH	= Colour, odor, texture; ↓ Taste	Bobinaite et al. (2016)
Mustard	Blueberry pomace	Powder/-	25 g/100 g	↑ TDF = TPC	↑ DPPH	↓ Appearance, color, aroma, flavor, texture, OA	Davis et al. (2018)
	Cranberry pomace	Powder/-	25 g/100 g	↑ TDF = TPC	↑ DPPH	↓ Appearance, color, aroma, flavor, texture, OA	Davis et al. (2018)
Pasta	Artichoke bracts	Extract/-	35.5 mL/100 g	↑ TPC	↑ ABTS	—	Pasqualone et al. (2017)

[a]Without overall significant differences or less pronounced differences when compared to the highest concentrations.
ABTS 2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) diammonium salt, *DPPH* diphenyl-1-picrylhydrazyl, *FRAP* ferric reducing antioxidant power, *OA* overall acceptability, *TAC* total anthocyanins content, *TPC* total phenolic content.

upon factors like the dosage, form of the by-product, and matrix in which the FVB is added.

The incorporation of FVB in foodstuff reintroduces these food processing by-products back to the food chain, minimizing the environmental and economic problems related to their generation. Hence, this can be considered as the main advantage of such a strategy. Additionally, the presence of high value-added compounds derived from FVB in food products could enhance consumer's acceptability. Nevertheless, the majority of the analyzed researches lacks the evaluation of FVB' toxicity, *in vivo* activity, and bioavailability, which is mandatory in order to assess if these novel products are safe and health promoting to consumers.

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