Dietary Fiber Concentrates from Fruit and Vegetable By-products: Processing, Modification, and Application as Functional Ingredients

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Received: 31 October 2017 / Accepted: 18 May 2018 / Published online: 31 May 2018
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Abstract

The food industry is continuously looking for new sources of dietary fiber (DF) to use as an ingredient due to its well-known health benefits associated to its consumption. Usually, DF used for this purpose is obtained from cereal products or their by-products; however, by-products produced from the fruit and vegetable industry have comparatively higher DF content with more diverse compositions. DF concentrates (DFC), obtained by the processing of fruit and vegetable by-products, are suitable for food formulations because of their unique technological functionalities and applicabilities, both closely related to the DF composition. This review describes the DF definition and analytical procedures for its quantification, the processing of fruit and vegetable by-products aimed to obtain high quality DFC, as well as the control of the processing conditions to obtain DFC with specific functionalities. Furthermore, it deals with the role of the modifications by thermal and non-thermal technologies, as well as of the application of DFC in several food formulations.

Keywords Dietary fiber processing · Dietary fiber concentrate · Functional properties · Fruit and vegetables by-products · Food ingredients

Abbreviations

AOAC	Association of Official Analytical Chemists
BD	Bulk density
CCNFSDU	Committee on Nutrition and Foods for Special Dietary Uses
DF	Dietary fiber
DFC	Dietary fiber concentrates
<i>dm</i>	Dry mass
FAO	Food and Agriculture Organization
HMSDF	High molecular weight soluble dietary fiber
or SDFP	
IDF	Insoluble dietary fiber

LMWSDF	Low molecular weight soluble dietary fiber or SDFS
NDO	Non-digestible oligosaccharides
OHC	Oil holding capacity
SC	Swelling capacity
SCFA	Short-chain fatty acids
SDF	Soluble dietary fiber
TDF	Total dietary fiber
WHC	Water holding capacity
<i>wm</i>	Wet mass
WSI	Water solubility index

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Introduction

An interest in the development of functional foods has emerged in recent years mainly because they can provide physiological and nutritional benefits. These foods contain ingredients which are known to provide beneficial effects on human health (Herrero et al. 2006). However, the functionality is not only related to health or physiology, but to physical or chemical modifications of a given food product which enhances specific desirable properties. The latter is also known as technological functionality. Dietary fiber (DF) has shown

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both functionalities and has become an important ingredient within the food industry due to its high applicability within food formulations.

In the last 40 years, several types of researches have been performed to demonstrate the health benefits attributed to the ingestion of DF, e.g., reduced risk for obesity, diabetes, and hypertension. For this reason, governments and international organizations have recently augmented the recommended daily DF intake up to 25 to 30 g for a 2000-kcal diet (European Food Safety Authority 2010; FDA 2014; Norma Oficial Mexicana 2010). Moreover, consumers are more concerned about the intake of healthy foods with high DF content and low caloric value. However, consumers also prefer non-synthetic ingredients obtained from natural resources. Furthermore, the food industry, in order to comply with the government recommendations and to satisfy the consumer's demands, is continuously looking for new DF sources.

Besides the high DF content, the food industry also seeks for low-cost DF sources with novel properties that allow obtaining food products with unique characteristics. In this context, the fruit and vegetable by-products seem to be a promising alternative. Furthermore, the use of these by-products contributes to the reduction of residues and wastes, which represents a serious environmental problem, around the world.

This review remarks the processing of plant by-products for the manufacturing of fiber-rich ingredients and the assessment of their functional properties and how these relate to the applied technologies and processing conditions. Moreover, this work covers the possible applications, nutraceutical properties, and technological functionalities of diverse fruit and vegetable by-products.

Dietary Fiber Definition and Determination Procedures

The definition of DF has been continually varying as a consequence of the advances in nutritional research, which claims physiological effects to new identified DF compounds, and on the development of new analytical procedures capable to include them all. This has historically resulted into several incongruences between the definition and the quantification techniques (DeVries et al. 2001). The concept of “dietary fiber” was first coined by Hipsley (1953) as a simple term to define the non-digestible compounds from plant foods included in the diet, which are an integral part of the vegetable cell wall. This definition included cellulose, hemicellulose, and lignin. Trowell et al. (1976) redefined the DF concept mainly based on the digestion resistance. In this definition, they embraced all the non-digestible carbohydrates, such as gums, modified cellulose, mucilage, oligosaccharides, and pectin. Since Trowell's definition, several research groups started to

develop analytical protocols that enabled the quantification of these new components in foods. All the generated methodologies were based on the removal of the digestible portions of the food using specific enzymes (Asp et al. 1983). Prosky et al. (1984) developed a precise methodology which was promptly adopted by the *Association of Official Analytical Chemists* (AOAC) as the official methodology for DF quantification (AOAC 985.29). This gravimetric assay is essentially based on the use of digestive enzymes to simulate digestion with the posterior quantitation of the undigested residue. In the early 1980s, Englyst et al. (1982) implemented a methodology to assess DF using gas-liquid chromatography. This chromatographic procedure quantified DF as non- α -glucans polysaccharides as the sum of all the monosaccharides released by acid hydrolysis after the removal of the enzymatically hydrolyzed starch. However, this methodology was not globally adopted because the chromatographic technique involved was too laborious for routine purposes (Asp et al. 1983) and besides it had low reproducibility (Champ et al. 2003). Lee et al. (1992) modified the AOAC 985.29 procedure by separating the DF into two fractions based on solubility. The first, which precipitates in water, is called insoluble dietary fiber (IDF); whereas the second, which is soluble in water but precipitates in 78% ethanol, is known as soluble dietary fiber (SDF). From the sum of both fractions, the total dietary fiber (TDF) is obtained. This methodology was readily adopted by the AOAC as the official procedure to quantify TDF and both fiber fractions (AOAC 991.43). Up to date, this is the most common method to assess DF in foods.

The definition of DF remained unchanged since the late 70s as “the remnants of edible plant cells, polysaccharides, lignin and associated substances resistant to digestion by the alimentary enzymes of humans.” This definition included cellulose, hemicellulose, lignin, gums, modified cellulose, mucilage, oligosaccharides, pectin, and minor associated substances, such as waxes, cutin, and suberin (DeVries 2004). However, some compounds comprised within that definition, such as resistant starch, some β -glucans, fructans, galactooligosaccharides, and polydextrose, among others, were not quantified by the official AOAC 991.43 technique, and have to be quantified by other AOAC official methods (2002.02, 995.16, 997.08, 2001.02, 2000.11, respectively), resulting in significant overestimations of DF (Asp et al. 1983). In order to include all these compounds in a single methodology, McCleary (2007) developed an integrated procedure, in which DF is measured as the sum of two fractions: the first with high molecular weight compounds (HMWDF) quantified gravimetrically with slight procedure differences than previous methodologies, and a second fraction formed with low molecular weight compounds (LMWDF), mainly non-digestible oligosaccharides (NDO), quantified by liquid chromatography (AOAC 2009.01). In 2009, the CODEX Alimentarius Commission, at the 31st meeting of the Codex Committee

on Nutrition and Foods for Special Dietary Uses (CCNFSDU), redefined the DF term as follows: “Dietary fibre means carbohydrate polymers with ten or more monomeric units, which are not hydrolyzed by the endogenous enzymes in the small intestine of humans.” A footnote in this definition indicates the inclusion of compounds, mainly from plant origin as long as they are quantified by AOAC methodologies, as well as with polymerization degree from three to nine, i.e., NDO. This definition includes the edible carbohydrate polymers that naturally occur in foods, the carbohydrate polymers obtained by physical, chemical, or enzymatic means, if the benefit to health is demonstrated, and synthetic carbohydrate polymers with proven health benefits (ALINORM 09/32/26 2008). In order to follow the CODEX definition, and to maintain the previous DF fractions based on solubility, McCleary modified in 2011 the AOAC 2009.01 methodology. The main changes consisted in separating the HMWDF into IDF, in high molecular weight soluble dietary fiber (HMWSDF or SDFP, due to its precipitation in 78% ethanol), and in low molecular weight soluble dietary fiber (LMWSDF or SDFS, due to its solubility in 78% ethanol). Finally, the TDF is obtained as the sum of the three fractions (IDF, SDFP, and SDFS) (McCleary et al. 2011). This methodology was adopted by AOAC as the official procedure 2011.25. Some studies have proved that more accurate fiber fraction contents are obtained using this methodology compared to those achieved with the AOAC 991.43 (Garcia-Amezquita et al. 2018; Hollmann et al. 2013).

Other non-enzymatic-gravimetric methodologies were developed based on the chemical properties of the fibrous compounds. The Weende method, with an acid and an alkali extraction, quantifies the sum of cellulose and lignin as “crude fiber,” this method only measured a fraction of the TDF (Asp et al. 1983; Yangilar 2013). The “Van-Soest method” allows quantifying the sum of cellulose, some hemicellulose, and lignin as “neutral-detergent fiber,” and “acid-detergent fiber” composed of cellulose and lignin (Van Soest and Wine 1967). A disadvantage of the use of these methodologies is that only IDF and a small part of SDF are quantified, leading to underestimation of the TDF value (Asp et al. 1983). Although these methodologies are still being used, they are not appropriate to quantify DF in foods (Champ et al. 2003).

Dietary Fiber Concentrates from Fruit and Vegetable By-products

Non-conventional Dietary Fiber Sources

Nowadays, there is an increasing trend to recover, recycle, and utilize industrial by-products. This trend has an enormous potential in the agricultural and food processing industries, mainly because the residues or by-products and effluents can be retrieved and reutilized, giving an added value to the main

production. The food processing industry is one of the largest, whereby the production and underutilization of its residues cause complications in environmental terms. Annually, more than 1.6 billion tons of foods are lost or wasted around the world, which causes not only great economic losses (approximately 750 billion USD) but also severe damage to natural resources. From this volume, approximately 1.4 billion tons come from plant sources, mainly cereals and vegetables (71%), followed by fruits (25%) and oilseed crops and legumes (4%). Approximately, 46% of these wastes are mainly due to losses during processing and distribution or the non-utilization of the entire products (FAO 2013). Moreover, in the case of plant origin foods, the considerable resources required for their production, such as water, energy, cropland, agrochemicals, are also misused when the food products are discarded. Usually, fruit and vegetable by-products are used to feed animals or simply incorporated into soils as organic matter or manure. However, a high amount of wastes cannot be used for these purposes because they are highly perishable (Herrero et al. 2006).

By-products produced from fruits and vegetables such as peels, seeds, and bagasse are of particular interest. In Table 1, the calculated amount of fruit by-products per year is shown considering the 2014 global production (FAO 2014) and the percentage of by-products generally obtained from each type of fruit. Some large fruit processing industries, such as the one that crushes orange juice, generate high amounts of by-products (50% of bagasse or waste) (Crizel et al. 2013; Marín et al. 2007). In the case of the more than 45 million tons of mango yearly produced worldwide, the fruit is mainly processed into nectar, puree, and juice generating ≈ 15 –20% of peels and ≈ 9 –23% of seed. Unfortunately, these by-products are usually discarded (Ajila et al. 2008). Pomace obtained after beetroot juice extraction is about 15–30% of the raw material (Schieber et al. 2001), whereas the tomato juice industry only generates approximately 3–7% by-products (peel and seeds bagasse) (Oreopoulou and Tzia 2007). However, tomato is one of the most produced vegetables; therefore, its industrialization yields considerable amounts of by-products. Some products generate even higher percentages of by-products that may be potentially used, such as prickly pear and passion fruit by-products which represent about 37–67% of peel and 10% of seeds (Jiménez-Aguilar et al. 2015), and 67% of the fruit rind (Schieber et al. 2001), respectively.

Besides the necessity to utilize agro-industrial wastes, fruit and vegetable by-products contain relevant amounts of bioactive phytochemicals, such as phenolic acids, flavonoids, lignans, and stilbenes with antimicrobial and antioxidant properties. Pulps contain ascorbic acid, as well as hydrophobic compounds with antioxidant activities, such as carotenoids and xanthophylls. Seeds are rich in phenolic compounds and tocopherols. In addition, the most abundant compound

Table 1 Annual world production of fruits and fruit by-products

Product	Annual global production in year 2014* million tons	Potential annual by-product production** million tons	Reference
Apple	25	9	(Oreopoulou and Tzia 2007)
Banana	114	34	(Schieber et al. 2001)
Beetroot	270	61	(Schieber et al. 2001)
Carrot	39	23	(Schieber et al. 2001)
Grape	75	15	(Schieber et al. 2001)
Kiwi	3	1	(Schieber et al. 2001)
Mango	45	27	(Ajila et al. 2008)
Orange	72	36	(Crizel et al. 2013)
Pineapple	25	8	(Tran and Mitchell 1995)
Potato	382	153	(Schieber et al. 2001)
Tomato	171	12	(Schieber et al. 2001)

*Data obtained from FAO 2014. **Calculated from the percentage of by-product obtained from each fruit mentioned in the references, and the annual global production

associated to by-products is DF (Ayala-Zavala et al. 2011) mainly composed of structural polysaccharides. Whereby, the use of fruit and vegetable by-products for the production of dietary fiber rich ingredients has recently gained attention.

Dietary Fiber Concentrates and Functional Properties

Dietary fiber can be obtained from an array of plant sources, such as grains, legumes, fruits and vegetables. According to Larrauri (1999), DF food ingredients must meet the following characteristics: high TDF (above 50%), low moisture and lipid content, low caloric value, and bland flavor when applied as an ingredient. Typically, DF is obtained from cereals and their by-products. However, the use of DF from fruits and vegetable sources must be considered because of their relatively higher SDF and TDF contents, lower phytic acid (except of DF obtained from some seeds) and caloric value, the enhanced colonic fermentability, and the improved functionality especially in terms of water and oil holding capacities (Amaya-Cruz et al. 2015; Figuerola et al. 2005; Larrauri 1999; Macagnan et al. 2015).

Currently, the food industry prefers to use low cost DF sources, obtained through the use of less severe processes to those traditionally applied in order to maintain its physiological potential, and improve the technological functionality as a food ingredient. In this regard, in the last 20 years, many researches have focused on the obtaining and characterization of such DF materials from fruit and vegetable by-products (Table 2). The term “dietary fiber concentrates” (DFC) was selected in this review for a product which major component is DF (> 50% *w*m), but which does not exclude the presence of other components, such as digestible carbohydrates, protein, lipids, minerals and a small amount of water (< 10% *w*m).

DFC are obtained by the dehydration of a fruit or vegetable by-product. DFC must not be confused with DF extracts, which are obtained by the removal of the fiber compounds from the original source through chemical or enzymatic methodologies. The main difference between them is their DF content: extracts usually have higher DF content than DFC. Additionally, extractions could be performed to obtain specific compounds such as arabinoxylans or β -glucans. Recently, Tejada-Ortigoza et al. (2016) described DF extraction procedures. Finally, the authors would like to highlight that the use of terms such as “flour” or “powder” to refer to DFC is avoided since these terms can be confused with cereal-based milled products and extracted DF compounds, respectively.

DFC can be obtained from by-products of diverse manufacturing processes (Table 2), like canning, beverage, and juice industries, among others. The juice processing industry probably produces the highest amount of by-products, mainly consisting in peels, and pomace; hence the obtaining of DFC from orange and apple peels are the most studied as depicted in Table 2. The content of TDF ranged between 17 and 92 g·100 g⁻¹ *dm*, [white grape skin (Deng et al. 2011) and date pulp (Elleuch et al. 2008) DFC, respectively]. DFC with high SDF:TDF ratios (*w*/*w*) were also reported, 0.80 and 0.76 for lemon and grapefruit pomaces DFC, respectively (López-Marcos et al. 2015).

DFC were first utilized as bulking agents in foods, i.e., to increase volume without raising the caloric value and costs. However, the interest on the functionality of DFC has led to study the characteristics provided when applied to foods. The most common functional properties of DFC are water and oil holding (WHC and OHC, respectively) capacities, swelling capacity (SC), water solubility index (WSI), and bulk density (BD). It is well known that functional properties depend on

Table 2 Soluble, insoluble, and total dietary fiber composition of dietary fiber concentrates obtained from fruit and vegetable by-products

Fruit/vegetable	By-product	Origin	SDF g·100 g ⁻¹ (dm)	IDF TDF	SDF:TDF	Reference
F R U I T S						
Apple	Peel	Fruit pulp industry	n.r.	69.6±0.6	n.r.	(Do Espirito Santo et al. 2012a)
	Pomace	Juice extraction	4.1±0.2	56.5±0.2	60.7±0.2	(Figuerola et al. 2005)
	Peel/pulp/seed pomace	Beverage industry	n.r.	n.r.	33.1±3.4	(O'Shea et al. 2015)
	Pomace	Juice extraction	8.2±0.2	81.6±0.2	89.8±0.2	(Figuerola et al. 2005)
	Pomace	Wine industry	11.1±0.9	59.8±4.9	70.9±1.3	(Cerdá-Tapia et al. 2015)
	Pomace	Juice extraction	14.3±0.6	63.9±0.2	78.2±0.6	(Figuerola et al. 2005)
Banana	Pomace	juice extraction	13.8±0.2	46.3±0.2	60.1±0.4	(Grigelmo-Miguel and Martín-Belloso 1999)
	Peel	Fruit pulp industry	n.r.	55.7±0.5	n.r.	(Do Espirito Santo et al. 2012a)
	Peel	Laboratory obtaining	7.3±0.7	30.3±1.2	37.6±1.5	(Agama-Acevedo et al. 2016)
	Peel	Laboratory obtaining	6.1±0.1	44.5±0.6	50.6±0.8	(García-Amezquita et al. 2018)
	Peel/pulp/seed	Juice extraction	1.6±0.8	46.0±0.9	47.5±0.1	(Crizel et al. 2016)
	Husk	Chocolate industry	10.1±0.4	50.4±0.7	60.5±0.3	(Lecumberri et al. 2007)
Blueberries	Defatted endosperm	Coconut milk extraction	5.0±n.r.	64.9±n.r.	69.9±n.r.	(Raghavendra et al. 2006)
Cocoa	bagasse	Laboratory obtaining	7.7±0.7	84.7±2.0	92.4±2.7	(Elleuch et al. 2008)
			6.7±1.4	81.3±0.9	88.0±1.6	(Elleuch et al. 2008)
Grapefruit	Flesh	Laboratory obtaining	56.3±2.8	18.1±0.9	74.3±0.6	(López-Marcos et al. 2015)
			6.4±0.5	37.8±0.2	44.2±0.4	(Figuerola et al. 2005)
Guava	Peel	Juice extraction	4.6±0.4	56.0±0.2	62.6±0.3	(Figuerola et al. 2005)
			8.0±n.r.	81.6±n.r.	89.6±n.r.	(Karaman et al. 2017)
Lemon	Defatted seed	Cold press oil extraction	11.1±0.1	57.7±0.2	69.1±0.2	(Martínez et al. 2012)
			57.8±2.8	14.5±0.8	72.4±0.5	(López-Marcos et al. 2015)
Lime	Peel/pulp/seeds	Juice industry	17.2±1.4	64.6±6.3	81.7±4.6	(Marín et al. 2007)
			9.2±0.2	50.9±0.2	60.1±0.2	(Figuerola et al. 2005)
Mamey sapote	Peel	Juice extraction	6.3±0.2	62.0±0.2	68.0±0.6	(Figuerola et al. 2005)
			6.5±n.r.	79.6±n.r.	86.1±n.r.	(Karaman et al. 2017)
Mango	Defatted seed	Cold press oil extraction	29.6±0.7	34.2±1.3	63.7±0.7	(Jongaroontrapangsee et al. 2007)
			32.2±1.1	40.2±0.6	72.4±0.5	(Peerajit et al. 2012)
Mango	Pomace	Laboratory obtaining	7.3±0.1	56.7±0.5	63.8±0.2	(García-Amezquita et al. 2018)
			15.7±0.2	21.2±0.5	37.1±0.5	(Amaya-Cruz et al. 2015)
Mango	peel	laboratory obtaining	15.2±1.0	25.4±2.4	40.5±1.6	(Tejada-Ortigoza et al. 2017a)
			18.1±0.6	22.7±2.8	42.5±1.7	(García-Amezquita et al. 2018)
Mango	peel/pulp	canning and juice industry	28.2±0.1	41.5±0.2	70.0±0.1	(Martínez et al. 2012)
			19.0±0.3	32.1±1.3	51.2±1.1	(Ajila et al. 2008)
Melon	peel	pulp processing industry	5.3±0.1	45.2±1.3	50.2±1.2	(Mallek-Ayadi et al. 2017)
			7.6±0.1	50.2±0.4	58.1±0.1	(García-Amezquita et al. 2018)
Meyer Lemon	peel	laboratory obtaining	4.3±0.4	49.3±1.4	53.7±1.0	(Crizel et al. 2016)
			17.4±1.3	46.2±2.3	63.6±0.9	(Crizel et al. 2013)
Orange	peel/ pulp/ seed	juice industry	15.6±1.5	48.2±1.6	63.7±0.1	(Crizel et al. 2013)
			7.1±n.r.	76.0±n.r.	83.0±n.r.	(Karaman et al. 2017)
Orange	defatted seed	cold press oil extraction	10.3±0.3	54.0±0.2	64.3±0.3	(Figuerola et al. 2005)
			n.r.	n.r.	45.2±1.3	(O'Shea et al. 2015)

Table 2 (continued)

Fruit/vegetable	By-product	Origin	SDF g-100 g ⁻¹ (dm)	IDF	TDF	SDF:TDF	Reference
<i>Citrus sinensis</i> cv Valencia	peel	laboratory obtaining	3.7 ± 0.6	45.7 ± 0.2	49.2 ± 0.4	0.08 : 1	(García-Amezquita et al. 2018)
<i>Citrus sinensis</i> cv Valencia	peel	laboratory obtaining	3.7 ± 0.1	47.1 ± 0.5	50.8 ± 0.3	0.07 : 1	(Tejada-Ortigoza et al., 2017a)
n.r.	pomace	juice extraction	13.6 ± 0.2	24.2 ± 0.4	37.8 ± 0.3	0.36 : 1	(Grigelmo-Miguel and Martín-Belloso 1999)
<i>Carica papaya</i>	peel	laboratory obtaining	1.9 ± 0.3	30.3 ± 0.2	32.2 ± 0.5	0.06 : 1	(Crizel et al. 2016)
<i>Passiflora edulis</i> cv Flavicarpa	seed/pulp pomace	juice extraction	5.3 ± n.r.	48.3 ± n.r.	53.5 ± n.r.	0.10 : 1	(López-Vargas et al. 2013)
<i>Passiflora edulis</i> cv Flavicarpa	Albedo	juice extraction	19.5 ± n.r.	52.3 ± n.r.	71.8 ± n.r.	0.27 : 1	(López-Vargas et al. 2013)
<i>Passiflora edulis</i> cv Flavicarpa	peel/ pulp/ seeds	canning and juice industry	35.5 ± 0.3	46.0 ± 0.1	81.5 ± 0.3	0.44 : 1	(Martínez et al. 2012)
<i>Passiflora edulis</i> cv Yellow	peel	fruit pulp industry	n.r.	n.r.	71.8 ± 0.6	n.r.	(Do Espírito Santo et al., 2012a)
Peach	pomace	juice extraction	9.7 ± 0.1	26.1 ± 0.2	35.8 ± 0.2	0.27 : 1	(Grigelmo-Miguel and Martín-Belloso 1999)
<i>Prunus persica</i>	peel/pomace/seed	juice industry	13.4 ± 0.0	24.3 ± 0.1	37.6 ± 0.1	0.36 : 1	(Amaya-Cruz et al. 2015)
Pear	pomace	juice extraction	14.1 ± 0.2	22.0 ± 0.2	36.1 ± 0.2	0.39 : 1	(Grigelmo-Miguel and Martín-Belloso 1999)
<i>Ananas comosus</i>	peel	juice industry	7.7 ± 2.0	37.6 ± 1.6	45.2 ± 0.4	0.17 : 1	(Crizel et al. 2016)
<i>Ananas comosus</i>	peel	pulp extraction	24.5 ± 1.8	46.2 ± 2.0	70.7 ± 3.6	0.35 : 1	(Díaz-Véla et al. 2013)
<i>Ananas comosus</i> cv MDII	peel/heart	canning and juice industry	0.6 ± 0.0	75.2 ± 0.2	75.8 ± 0.2	0.01 : 1	(Martínez et al. 2012)
<i>Punica granatum</i>	pomace	juice extraction	29.4 ± 1.5	27.0 ± 1.3	56.3 ± 0.4	0.52 : 1	(López-Marcos et al. 2015)
<i>Punica granatum</i> v Mollar de Elche	aril bagasse	juice extraction	16.6 ± 0.1	29.0 ± 0.5	45.6 ± 0.2	0.36 : 1	(Viuda-Martos et al. 2012)
<i>Punica granatum</i> v Mollar de Elche	peel/aril bagasse	juice extraction	19.9 ± 0.3	30.4 ± 0.4	50.3 ± 0.3	0.40 : 1	(Viuda-Martos et al. 2012)
<i>Opuntia ficus-indica</i>	peel	pulp extraction	33.9 ± 1.7	37.0 ± 1.8	71.0 ± 2.3	0.48 : 1	(Díaz-Véla et al. 2013)
<i>Opuntia ficus-indica</i> cv Verde Villanueva	peel	laboratory obtaining	7.0 ± 0.3	31.2 ± 0.5	38.1 ± 0.5	0.18 : 1	(García-Amezquita et al. 2018)
<i>Opuntia ficus-indica</i> cv Verde Villanueva	peel	laboratory obtaining	8.5 ± 0.2	32.6 ± 0.2	41.0 ± 0.2	0.21 : 1	(Tejada-Ortigoza et al. 2017a)
<i>Vitis vinifera</i> cv Cabernet Sauvignon	skin pomace	wine industry	0.8 ± 0.1	52.4 ± 0.4	53.2 ± 0.4	0.02 : 1	(Deng et al. 2011)
<i>Vitis vinifera</i> cv Manto negro	stem	wine industry	3.8 ± 0.2	73.5 ± 1.8	77.2 ± 2.0	0.05 : 1	(Llobera and Cañellas 2007)
<i>Vitis vinifera</i> cv Manto negro	pomace	wine industry	10.8 ± 0.3	63.7 ± 2.1	74.5 ± 2.4	0.14 : 1	(Llobera and Cañellas 2007)
<i>Vitis vinifera</i> cv Merlot	skin pomace	wine industry	1.5 ± 0.1	49.6 ± 0.4	51.1 ± 0.6	0.03 : 1	(Deng et al. 2011)
<i>Vitis vinifera</i> cv Pinot Noir	skin pomace	wine industry	1.7 ± 0.2	54.6 ± 1.6	56.3 ± 1.5	0.03 : 1	(Deng et al. 2011)
<i>Vitis vinifera</i> cv Pinot Noir	whole fruit residue	flavonoids extraction industry	3.1 ± 0.2	74.6 ± 7.0	77.7 ± 4.9	0.04 : 1	(Marín et al. 2007)
<i>Citrus aurantium</i>	peel	juice extraction	9.4 ± 0.1	47.6 ± 1.1	57.0 ± 1.0	0.17 : 1	(Chau and Huang 2003)
<i>Citrus sinensis</i> cv. Liucheng	pomace	juice extraction	17.3 ± 0.2	46.5 ± 0.3	63.8 ± 0.1	0.27 : 1	(Huang and Ma 2016)
<i>Cyperus excultus</i>	bagasse	horchata elaboration	0.1 ± n.r.	64.6 ± 3.3	67.7 ± 0.6	0.00 : 1	(López-Marcos et al. 2015)
<i>Tamarindus indica</i>	pericarp/pods	laboratory obtaining	3.9 ± 0.2	59.7 ± 0.8	63.5 ± 0.8	0.06 : 1	(García-Amezquita et al. 2018)
<i>Lycopersicon esculentum</i>	peel	food processing industry	14.3 ± 0.4	71.8 ± 0.8	86.2 ± 0.6	0.17 : 1	(Navarro-González et al. 2011)
<i>Citrullus lanatus</i>	rind	fresh-cut fruit producer	19.1 ± n.r.	53.1 ± n.r.	72.3 ± n.r.	0.26 : 1	(Naknaen et al. 2016)
<i>Citrullus lanatus</i>	rind	laboratory obtaining	3.2 ± 0.0	38.2 ± 0.6	41.5 ± 0.8	0.08 : 1	(García-Amezquita et al. 2018)
<i>Vitis vinifera</i> cv Morio Muscat	skin pomace	wine industry	0.8 ± 0.1	16.4 ± 0.2	17.3 ± 0.2	0.05 : 1	(Deng et al. 2011)
<i>Vitis vinifera</i> cv Muller Thurgau	skin pomace	wine industry	0.7 ± 0.1	27.3 ± 1.5	28.0 ± 1.4	0.03 : 1	(Deng et al. 2011)
<i>Vitis vinifera</i> cv Prensall Blanc	stem	wine industry	3.9 ± 0.2	75.1 ± 3.1	79.1 ± 3.3	0.05 : 1	(Llobera and Cañellas 2008)
<i>Vitis vinifera</i> cv Prensall Blanc	pomace	wine industry	10.3 ± 0.3	61.3 ± 2.2	71.6 ± 2.5	0.14 : 1	(Llobera and Cañellas 2008)
<i>Psidium guajava</i>	peel/pomace/seed	juice industry	4.3 ± 0.4	74.4 ± 0.2	78.4 ± 0.3	0.05 : 1	(Amaya-Cruz et al. 2015)
V E G E T A B L E S							
Artichoke	peel	canning process	14.3 ± 0.3	44.5 ± 0.3	58.8 ± 0.6	0.24 : 1	(Grigelmo-Miguel and Martín-Belloso 1999)
<i>Asparagus officinalis</i> L.	stem	canning process	9.9 ± 1.7	58.2 ± 1.9	68.1 ± 3.6	0.15 : 1	(Fuentes-Alventosa et al. 2009)
n.r.	peel	canning process	10.4 ± 0.6	38.6 ± 0.2	49.0 ± 2.6	0.21 : 1	

Table 2 (continued)

Fruit/vegetable	By-product	Origin	SDF g·100 g ⁻¹ (dm)	IDF	TDF	SDF:TDF	Reference
Carrot	peel	ready-to-eat vegetable industry	10.3 ± 0.1	38.9 ± 3.6	49.2 ± 3.5	0.21 : 1	(Grigelmo-Miguel and Martín-Belloso 1999)
Maca	root bagasse	liquor obtaining	3.5 ± 0.2	37.4 ± 2.3	40.9 ± 2.3	0.09 : 1	(Chen et al. 2015)
Onion	bagasse	onion industry	8.8 ± 0.4	27.3 ± 2.0	36.1 ± 1.4	0.24 : 1	(Benítez et al. 2011)
	bagasse	onion industry	4.6 ± 0.4	40.7 ± 0.7	45.3 ± 0.6	0.10 : 1	(Benítez et al. 2011)
Potato	peel	potato chips industry	2.6 ± 0.7	24.0 ± 0.8	26.6 ± 0.1	0.10 : 1	(Camire et al. 1997)
White cabbage	outer leaves	laboratory obtaining	4.9 ± 0.3	38.3 ± 5.2	43.2 ± 5.6	0.11 : 1	(Jongaroontrapangsee et al. 2007)

n.r.: non-reported value

both, the SDF:IDF ratio (Viuda-Martos et al. 2012), and the chemical composition of DF. Marín et al. (2007) observed in DFC from citrus by-products an increment of WHC (from ≈ 1 to $8 \text{ mL} \cdot \text{g}^{-1}$) and OHC (from ≈ 0.12 to $0.34 \text{ g} \cdot \text{g}^{-1}$), related to higher SDF (from ≈ 1 to $25 \text{ g} \cdot 100 \text{ g}^{-1}$) and lignin (from ≈ 3 to $17 \text{ g} \cdot 100 \text{ g}^{-1}$) content, respectively. Nonetheless, different results were published by Crizel et al. (2013) who observed a lower WHC value ($8.7 \text{ mL} \cdot \text{g}^{-1}$) in a DFC from orange bagasse (containing peel, pulp, and seeds) with a SDF content of $17.4 \text{ g} \cdot 100 \text{ g}^{-1} \text{ dm}$, compared to that in DFC from orange peel ($9.6 \text{ mL} \cdot \text{g}^{-1}$) with a lower DF content ($15.6 \text{ g} \cdot 100 \text{ g}^{-1} \text{ dm}$). These observations may help to design ingredients for specific applications in foods, adjusting certain components of DFC. However, it is important to note that DFC are not pure-fiber materials and other compounds, such as proteins, lipids or digestible carbohydrates, may influence on the functional properties. Thereby, not all these properties can be attributed to the DF content and composition.

Preparation of Dietary Fiber Concentrates

The flowchart with the most relevant unit operations for the production of DFC from fruit by-products is depicted in Fig. 1. It is important to highlight that not all the steps are always needed and depend on the raw material state, and the desired finished properties of the DFC.

Packing, Frozen and Thawing Commonly, the food industries do not spend large amount of resources to preserve by-products and they must be collected just in time after the industrial processing. However, if the preparation of DFC is not conducted immediately, it is recommended to vacuum pack by-products in polyethylene and polyamide pouches with low water vapor permeability ($1.1 \text{ g} \cdot \text{m}^{-2} \cdot 24 \text{ h}^{-1}$ at 23°C) (Fernández-Ginés et al. 2003), followed by freezing (-30 to -4°C) storage. To avoid deterioration of the organic material by microorganisms (Do Espírito Santo et al. 2012a), enzymes or oxidation reactions, thawing must be conducted at temperatures of 2 to 5°C . Several DFC obtaining procedures mentioned a thawing time of 24 h in this range of temperatures (Fernández-Ginés et al. 2003; Fernández-López et al. 2004; Marín et al. 2007).

Chopping When the size of by-products size is too big, such as in watermelon residues, melon rinds and pineapple peels and heart (Díaz-Vela et al. 2013; Mallek-Ayadi et al. 2017; Naknaen et al. 2016), it is recommended to cut them into smaller pieces for better handling. Occasionally, by-products are blended to produce a paste before drying in order to increase the contact surface and facilitate the dehydration process. In this step, some fractions could be separated to obtain DFC with specific characteristics. Lopez-Vargas et al. (2013) utilized the passion fruit albedo to produce a DFC with high

Fig. 1 Process flowchart of the general steps to prepare dietary fiber concentrates from fruit and vegetable by-products

SDF ($19.4 \text{ g} \cdot 100 \text{ g}^{-1} \text{ dm}$) compared to a DFC prepared from pulp and seeds ($5.3 \text{ g} \cdot 100 \text{ g}^{-1} \text{ dm}$). Likewise, Crizel et al. (2013) compared DFC obtained from juice industry by-products, DFC from orange peel (only albedo and flavedo fractions) showed higher WHC, OHC and solubility values than DFC from orange bagasse (peel, pulp, and seeds).

Washing This step is usually used for both removing particles from by-products (Ajila et al. 2008), and to decrease contents of soluble compounds, such as free sugars, ashes, and some proteins. However, some desirable compounds, like pectin or antioxidants associated with the fiber such as flavonoids, may also be lost (Larrauri 1999; Marín et al. 2007). This operation unit is not always used because of the reduction in the SDF fraction of the DFC, but its application results in DFC with higher TDF content and lower caloric value. Additionally, the reduction of the sugar content is recommended to modify the collapse temperature during freeze-drying, if used, to decrease stickiness and caking during grinding (Ratti 2013), and to reduce browning if hot air drying is applied. Both the water temperature and the washing time are critical. Larrauri et al. (1996) observed a reduction of up to 23% on the SDF content when the washing time was increased from 5 to 10 min. High temperatures during washing might decrease the free sugars on the final DFC (Larrauri 1999) and low temperature is recommended to minimize losses of SDF (mainly pectins and pentosans) as well of flavonoids, phenolic acids, and tannins (Martínez et al. 2012). The reduction of free sugars and SDF compounds by washing modifies hydration properties increasing the WHC of the DFC (Jongaroontaprangsee et al. 2007).

Blanching or Scalding Similarly to washing, one of the purposes of scalding is to remove undesirable compounds associated with dietary fiber (i.e., sugars, ashes, and dirt particles, among others). The use of high temperatures (above 90°C) during this step reduces SDF content. Marín et al. (2007) observed a reduction in pectin content of up to 58% in citrus DFC produced by the scalding process, resulting in a decrease in the SDF content of 54%; furthermore, the severe thermal treatment on citrus by-products unfortunately diminished levels of flavonoids and ascorbic acid and consequently the antioxidant activity of the DFC. Besides the undesirable particles removal, the main objective of blanching is to inactivate potentially pathogenic microorganisms (vegetative cells) (Fernández-López et al. 2004) and to inactivate undesirable proteolytic enzymes (Sah et al. 2016) and the ones responsible for browning reactions, such as polyphenol oxidases and peroxidases (Chantaro et al. 2008). On the other hand, blanching reduces the hot air drying time. Peerajit et al. (2012) reduced dehydration time from 10.5 to 8 h on the obtaining of lime residue DFC previously blanched at 95°C for 5 min. The results suggest a structural softening of the lime by-product produced by the hot water. After washing or blanching steps,

the by-products retain a considerable amount of water and should be pressed or centrifuged to remove excess water and reduce the drying time (Fernández-López et al. 2004; Peerajit et al. 2012; Viuda-Martos et al. 2012).

Drying In general, there are three purposes to dehydrate by-products before DFC production, the first is to improve the DFC shelf-life without the use of chemical preservatives by the reduction of the water activity (Marín et al. 2007; Viuda-Martos et al. 2012), the second is aimed to concentrate the DF which is the main component of fruit and vegetable by-products, and finally to obtain a more manageable product, reducing the volume of the material, and increasing its applicability as ingredient in food processing. This operation may be conducted by several techniques to remove water from the matrix; however, this section focusses only on hot air drying and freeze drying since most DFCs are obtained experimentally or industrially using mainly these dehydration procedures, so for example all the DFC mentioned in Table 2 has been obtained using these drying processes.

Hot Air Drying This step can be performed using convective air oven, tray, cross flow dryer, or tunnel dryers. The control variables to optimally obtain DFC are air temperature and residence time. Several studies have shown that a temperature between 40 and 50°C is enough to reach moisture content to less than $10 \text{ g} \cdot 100 \text{ g}^{-1}$ (Agama-Acevedo et al. 2016; Ajila et al. 2008; Chau and Huang 2003; Marín et al. 2007). However, the most applied temperatures to obtain constant weight ranged between 55 and 60°C (Crizel et al. 2015, 2016; Do Espírito Santo et al. 2012a; Martínez-Cervera et al. 2011; Naknaen et al. 2016; Peerajit et al. 2012). Moreover, the low transition temperature (T_g) of products with high sugar content must be considered; consequently, drying fruit by-products with temperatures above 60 – 65°C could result in materials with sticky or leathery texture due to the plasticizing effect of the low molecular weight sugars (B. R. Bhandari and Howes 1999). The use of higher drying temperatures to obtain DFC have been reported in some studies; however, it is only used to evaluate the effect of temperature and to obtain drying kinetics (Chantaro et al. 2008; Jongaroontaprangsee et al. 2007; Vega-Gálvez et al. 2015), and its use is not recommended. Vega-Gálvez et al. (2014) observed that the time required to achieve a moisture ratio of 0.1 in the production of cape-gooseberry DFC at 90°C was 180 min compared to more than 800 min needed at 50°C .

The effect of drying temperature on the DF content and composition is not clear. A slight decrement of TDF was observed in DFC obtained from carrot peels (Chantaro et al. 2008) and cabbage outer leaves (Jongaroontaprangsee et al. 2007). However, drying temperature certainly modified functional properties as shown in Fig. 2. Studies performed with carrot peel (Chantaro et al. 2008), orange peel (Garau et al.

Fig. 2 Effect of drying temperature of dietary fiber concentrates obtained from orange peel (●) (Garau et al. 2007), carrot peel (○) (Chantaro et al. 2008), lime residue (■), and outer cabbage leaves (◐) (Jongaroontaprangsee et al. 2007) on **a** water holding capacity (WHC), **b** oil holding capacity (OHC), **c** swelling capacity (SC), and **d** water solubility index (WSI)

2007), and lime residue (Jongaroontaprangsee et al. 2007) have shown that WHC, OHC, and WSI values were higher when mild temperatures (40 to 60 °C) were used; whereas at lower drying temperature (below 40 °C) and higher (above 60 °C) DFC decreased their WHC and WSI properties, while OHC only decreased when temperatures above 80 °C were applied. The SC seemed to be unaffected by drying temperature.

Freeze-drying This is the operation whereby water is removed from a food product by sublimation and desorption, and the process is conducted in frozen food product (Garcia-Amezquita et al. 2016). The recommended frozen temperatures depend on the sugar content and composition of the by-product laying between −40 and −80 °C (Ratti 2013). High-temperature treatments have a significant effect on the DF content, composition and functionality of DFC; for this reason, the use of freeze-drying is preferred instead of hot air drying. Furthermore, the use of this dehydration process improves the preservation of the powder's microstructure (Garcia-Amezquita et al. 2016). Fuentes-Alventosa et al. (2009) observed that freeze-dried DFC maintained more soluble sugars content, as well as higher WSI (29%) and OHC (11%) values compared to counterparts dried with hot air. Nonetheless, the major withdrawal of freeze-drying, especially taking into consideration that DFC should be produced at relatively low costs, is that is an expensive and a long lasting batch method.

Dry Milling and Sieving Dehydrated by-products are commonly industrially milled with hammer, Wiley, or disc mills. Sieving the powders could be preferably performed during the milling operation; otherwise, the ground powder must be sieved after grinding to obtain powders with a specific particle size distribution. Most of the reviewed studies produced

powders with a particle size below 425 µm (US Mesh 40). The reason for using this is probably to facilitate the DF quantification since AOAC methodologies (985.25, 991.43, 2009.01, and 2011.25) establish that value. However, the particle size mainly depends on the application of the powder. It has been observed that powders with smaller particle sizes are easier integrated to dairy products, whereas bakery, meat, or extruded snacks products do not require fine powders. Do Espírito Santo et al. (2012a) incorporated passion fruit DFC to yogurt sieved with a 42-µm opening mesh. Crizel et al. (2014) produced lemon ice cream with orange peel DFC with a particle size below 125 µm, and Dhingra et al. (2012) baked biscuits with potato peel DFC sieved with a No. 100 mesh (opening 150 µm).

On the other hand, the particle size has a significant effect on the functional properties of the DFC. As shown in Fig. 3, WHC increases with larger particle size. Sangnark and Noomhorm (2003) observed an increment of about 64% increasing the particle size of sugarcane bagasse DFC from 75 to 300 µm; whereas, Jongaroontaprangsee et al. (2007) remarkably increased almost 300% this property in cabbage outer leaves DFC when increasing the particle size from a range of 63–150 µm to 300–450 µm. SC is also affected by particle size. For instance, studies conducted in carrot peel (Chantaro et al. 2008) and outer cabbage leaves (Jongaroontaprangsee et al. 2007) DFC showed an increase of SC in the range of 100 to 500 µm; however, Raghavendra et al. (2006) reported a decrease in SC of coconut residue DFC when increasing the particle size above 550 µm. Finally, studies performed with coconut residues (Raghavendra et al. 2006) and lemon pomace (Lario et al. 2004) DFC have proved that OHC remains constant at high particle sizes, and decreases with DFC milled below 400 µm (Sangnark and Noomhorm 2003).

Fig. 3 Effect of particle size of dietary fiber concentrates obtained from lime residue (●) and cabbage outer leaves (○) (Jongaroontaprangsee et al. 2007), coconut endosperm bagasse (■) (Raghavendra et al. 2006), sugarcane bagasse (□) (Sangnark and Noomhorm 2003), and lemon by-products (*) (Lario et al. 2004) on **a** water holding capacity (WHC), **b** swelling capacity (SC), and **c** oil holding capacity (OHC)

Packaging and Storage After processing, packaging and storage of DFC are optional operations (Agama-Acevedo et al. 2016; Fernández-López et al. 2004). DFC should be packaged in vacuum-sealed pouches (polyethylene or polypropylene

bags may be used), and stored before usage. It is recommended to store at refrigeration temperatures to reduce deteriorative reactions, and preferably under darkness conditions to avoid lipid photo-oxidation or degradation of relevant antioxidants such as flavonoids and carotenoids (Fernández-López et al. 2004). Finally, an additional treatment using UV irradiation (30 min) could be applied to avoid microbial growth during storage. This step is highly necessary if DFC is used for fermented products such as yogurts (Sah et al. 2016).

Seeds Processing Although usually seeds are discarded for the obtaining of DFC due to their high lipid content, their DF content is considerable high and therefore could represent a good feedstock to prepare concentrates. Seeds must be firstly roasted (30 min) to inhibit germination enzymes. A defatting process is needed to remove lipids. This step could be conducted using cold pressing or by solvent extraction, usually hexane. Karaman et al. (2017) reported that DFC from lemon, orange and grapefruit seeds defatted with hexane contained lower SDF than cold-pressed seeds. As expected, these differences also impacted the WHC, OHC and SC values.

Liquid By-products Processing Occasionally effluents can be obtained from the food industry, or even from any other step of the preparation of DFC. These liquid by-products have high SDF and therefore could be further processed into NDO and DFC with adequate levels of prebiotics. Sánchez-Zapata et al. (2013) obtained a DFC from tiger nut effluent liquid by pressing the residual nut from the “horchata” preparation. A prebiotic study clearly demonstrated that the liquid by-product increased the probiotic population in the hindgut.

Modification Processes of the Composition and Functionality of Dietary Fiber Concentrates

The technological and nutraceutical functionality of DF depends on both the fiber composition and the SDF:IDF ratio. Different technologies have been applied to purposely modify the SDF and IDF contents or ratios. In this regard, chemical and enzymatic modifications are the most used. These technologies promote the partial hydrolysis of the polysaccharides, thereby changing their functionality, and usually are followed by a purification process to obtain the modified fibrous material (Tejada-Ortigoza et al. 2016). However, traditional extraction methods are not desirable for DFC since (as explained in section 2) the methodologies may cause undesirable changes. In this context, several traditional and emerging technologies have been studied to modify the DF composition of DFC (Table 3) and consequently their functional properties (Table 4).

Table 3 Dietary fiber composition modification of dietary fiber concentrates obtained from fruit and vegetable by-products using different technologies

Source	Processing conditions	Dietary fiber composition				Increment/decrement*				Reference
		SDF g/100 g ⁻¹ (dm)	IDF	TDF	SDF:TDF	SDF %	IDF	TDF	SDF:TDF	
Extrusion										
Potato peel	Untreated (abrasion peeled)	2.6 ± 0.7	24.0 ± 0.8	26.6 ± 0.1	0.10 : 1	161	-23	-5	174	Camire et al. 1997
	150 °C - 30% moisture - 300 rpm	6.8 ± 0.6	18.6 ± 1.1	25.4 ± 1.4	0.27 : 1					
Sweet orange pomace	Untreated	17.3 ± 0.2	46.5 ± 0.3	63.8 ± 0.1	0.27 : 1	74	-28	0	74	Huang and Ma, 2016
	125 °C - 14% moisture - 290 rpm	30.1 ± 0.3	33.5 ± 0.1	63.6 ± 0.1	0.47 : 1					
Orange pulp	Untreated	20.1 ± n.r.	54.8 ± n.r.	74.9 ± n.r.	0.27 : 1	89	-40	-6	100	Larrea et al. 2005a
	150 °C - 35% moisture - 140 rpm	37.9 ± n.r.	32.7 ± n.r.	70.6 ± n.r.	0.54 : 1					
Lime pomace	Untreated	38.6 ± n.r.	57.0 ± n.r.	95.6 ± n.r.	0.40 : 1	30	-16	2	26	Méndez-García et al. 2011
	100 °C - 40% moisture - 10 rpm	50.0 ± n.r.	48.0 ± n.r.	98.0 ± n.r.	0.51 : 1					
Thermal										
Onion (cv Recas) bagasse	Untreated	4.6 ± 0.4	40.7 ± 0.7	45.3 ± 0.6	0.10 : 1	163	-29	-10	192	Benítez et al., 2011
	Autoclave (115 °C - 26 min)	12.1 ± 0.4	28.7 ± 0.8	40.8 ± 0.6	0.30 : 1					
Potato peel	Abrasion peeling	2.6 ± 0.7	24.0 ± 0.8	26.6 ± 0.1	0.10 : 1	107	113	112	-3	Camire et al. 1997
	Steam peeling	5.4 ± 0.5	51.1 ± 1.3	56.5 ± 2.2	0.10 : 1					
Carrot peel	Untreated	10.3 ± 0.1	38.9 ± 3.6	49.2 ± 3.5	0.21 : 1	84	40	49	23	Chantaro et al., 2008
	Blanching (90 °C - 1 min)	19.0 ± 2.5	54.3 ± 1.1	73.3 ± 1.4	0.26 : 1					
Lime pomace	Untreated	39.2 ± 6.5	43.4 ± 0.8	82.6 ± 6.3	0.47 : 1	-26	-10	-18	-10	Jongaroonlapangsee et al. 2007
	Blanching (90 °C - 5 min)	29.1 ± 1.9	39.0 ± 2.2	68.2 ± 0.3	0.43 : 1					
Orange peel	Untreated	7.2 ± 0.6	46.3 ± 1.2	52.5 ± 0.5	0.14 : 1	73	-84	-5	82	Tejada-Ortigoza et al. 2017b
	Heating (70 °C - 42 min)	12.4 ± 1.2	7.5 ± 0.5	49.8 ± 1.9	0.25 : 1					
Sour orange pomace	Untreated	6.8 ± 0.5	56.0 ± 5.2	62.8 ± 3.7	0.11 : 1	-54	33	24	-63	Marín et al., 2007
	Scalding (boiling water - < 1 min)	3.1 ± 0.2	74.6 ± 7.0	77.7 ± 4.9	0.04 : 1					
Lemon pulp pomace	Untreated	23.3 ± 1.8	54.0 ± 4.2	77.3 ± 3.2	0.30 : 1	-26	19	6	-30	
	Scalding (boiling water - < 1 min)	17.2 ± 1.4	64.6 ± 6.3	81.7 ± 4.6	0.21 : 1					
High pressure										
Mango peel	Untreated	15.2 ± 1.0	25.4 ± 2.4	40.5 ± 1.6	0.37 : 1	15	-16	-4	20	Tejada-Ortigoza et al. 2017a
	600 MPa - 10 min	17.5 ± 1.2	21.4 ± 0.4	38.9 ± 1.0	0.45 : 1					
Orange peel	Untreated	3.7 ± 0.1	47.1 ± 0.5	50.8 ± 0.3	0.07 : 1	59	-8	-4	64	
	600 MPa - 10 min	5.9 ± 0.2	43.1 ± 0.3	49.0 ± 0.2	0.12 : 1					
Cactus pear peel	Untreated	8.5 ± 0.2	32.6 ± 0.2	41.0 ± 0.2	0.21 : 1	22	9	12	9	
	600 MPa - 10 min	10.3 ± 0.7	35.5 ± 1.2	45.9 ± 0.9	0.23 : 1					
High pressure/thermal										
Orange peel	Untreated	7.2 ± 0.6	46.3 ± 1.2	52.5 ± 0.5	0.14 : 1	94	-16	0	94	Tejada-Ortigoza et al. 2017b
	600 MPa - 70 °C - 20 min	13.9 ± 0.6	38.8 ± 1.1	52.6 ± 1.4	0.26 : 1					

*Negative values indicate decrement in the soluble (SDF), insoluble (IDF), and total (TDF) dietary fiber value. n.r.: non-reported values

Table 4 Functional properties modification of dietary fiber concentrates obtained from fruit and vegetable by-products using different technologies

Source	Processing conditions	WHC		OHC		SC		WSI		BD	Increment/decrement*				Reference
		mL·g ⁻¹	mL·g ⁻¹	mL·g ⁻¹	mL·g ⁻¹	%	%	WHC							
								%	g·mL ⁻¹		WSI	BD			
Extrusion															
Sweet orange pomace	Untreated	5.8 ± 0.0	1.2 ± 0.0	8.3 ± 0.1	27.8 ± 0.1	0.59 ± 0.01	16	-32	85	10	31	Huang and Ma, 2016			
	125 °C - 14% moisture - 290 rpm	6.7 ± 0.0	0.8 ± 0.4	15.3 ± 0.1	30.6 ± 0.5	0.77 ± 0.00									
Orange pulp	Untreated	n.r.	n.r.	16.0 ± n.r	12.5 ± n.r	n.r.	n.r.	n.r.	44	134	n.r.	Larrea et al. 2005b			
	150 °C - 25% moisture - 140 rpm	n.r.	n.r.	23.0 ± n.r	29.3 ± n.r	n.r.									
Thermal															
Onion (cv Recas) bagasse	Untreated	6.7 ± 0.3	4.3 ± 0.1	21.0 ± 0.3	n.r.	0.35 ± 0.01	-4	-7	-10	n.r.	66	Benítez et al., 2011			
	Autoclave (115 °C - 26 min)	6.4 ± 0.4	4.0 ± 0.0	19.0 ± 0.2	n.r.	0.58 ± 0.00									
Carrot peel	Untreated (300–450 µm)	15.5 ± 0.3	n.r.	19.0 ± 1.6	n.r.	n.r.	36	n.r.	80	n.r.	n.r.	Chantaro et al., 2008			
	Blanching (90 °C - 1 min)	21.1 ± 1.2	n.r.	34.1 ± 0.3	n.r.	n.r.									
Orange peel	Untreated	3.9 ± 0.1	1.8 ± 0.1	8.1 ± 0.2	34.1 ± 0.8	0.55 ± 0.02	0	50	-5	8	-1	Tejada-Ortigoza et al. 2017b			
	Heating (70 °C - 42 min)	3.9 ± 0.0	2.7 ± 0.1	7.7 ± 0.3	36.7 ± 1.2	0.54 ± 0.03									
High pressure															
Mango peel	Untreated	13.1 ± 1.6	1.0 ± 0.5	11.2 ± 0.7	82.2 ± 1.2	0.59 ± 0.01	4	-50	-6	2	21	Tejada-Ortigoza et al. 2017a			
	600 MPa - 10 min	13.6 ± 2.3	0.5 ± 0.1	10.5 ± 0.3	83.9 ± 1.3	0.71 ± 0.00									
Orange peel	Untreated	6.0 ± 1.0	1.3 ± 0.1	9.3 ± 0.2	55.1 ± 1.7	0.43 ± 0.00	-10	-44	-18	0	30				
	600 MPa - 10 min	5.4 ± 0.4	0.7 ± 0.0	7.6 ± 0.2	55.3 ± 0.9	0.55 ± 0.01									
Cactus pear peel	Untreated	10.9 ± 1.3	1.0 ± 0.0	13.0 ± 0.1	78.3 ± 1.8	0.47 ± 0.01	63	-41	-5	-14	40				
	600 MPa - 10 min	17.8 ± 2.2	0.6 ± 0.1	12.4 ± 0.5	67.1 ± 2.1	0.66 ± 0.00									
High pressure/thermal															
Orange peel	Untreated	3.9 ± 0.1	1.8 ± 0.1	8.1 ± 0.2	34.1 ± 0.8	0.55 ± 0.02	-10	15	-14	4	-1	Tejada-Ortigoza et al. 2017b			
	600 MPa - 70 °C - 20 min	3.5 ± 0.1	2.0 ± 0.1	7.0 ± 0.3	35.5 ± 0.6	0.54 ± 0.00									

*Negative values indicate decrement on water holding capacity (WHC), oil holding capacity (OHC), swelling capacity (SC), water solubility index (WSI), and bulk density (BD). n.r.: non-reported values

Extrusion Extrusion processing effectively modifies the DF fractions composition and consequently also the DFC functionality. The factors that affect the modifications are the applied temperature gradients, the tempering or conditioning moisture of the feedstock and the shear produced by the screw(s) design. Larrea et al. (2005a) studied the effect of different extrusion conditions (temperature 83–167 °C, feeding moisture 22–38%, and screw speed 126–194 rpm) on the DF fractions of orange pulp pomace. They observed a slight reduction in TDF content for all treatments; however, a maximum increase of 89% on the SDF fraction (from 20.1 to 37.9 g·100 g⁻¹ dm, untreated and extruded, respectively) was achieved when processing the feedstock at 35% moisture, 150 °C, and 140 rpm. A similar trend was observed by Méndez-García et al. (2011) who found an increment of up to 30% of the SDF fraction in lime pomace (from 38.6 to 50.0 g·100 g⁻¹ dm, untreated and extruded, respectively) extruded at 110 °C and 30% moisture. Huang and Ma (2016) studied the effect of extrusion conditions in orange pomace using a single screw laboratory scale extruder (temperature 115–135 °C, feeding moisture 10–18%, and screw speed 230–350 rpm). Results of their study indicated that the SDF increased up to 74% (from 17.3 to 30.1 g·100 g⁻¹ dm, untreated and extruded, respectively) when processing at 125 °C, 14% moisture, and 290 rpm. A research conducted on extruded soybean residue showed that the additional amount of SDF after extrusion was similar to the reduced IDF content, suggesting that the improved SDF is caused by a partial solubilization of the IDF without a complete degradation of the polymeric structure (Jing and Chi 2013). Moreover, Huang and Ma (2016) observed an increase in the monosaccharides xylose, mannose, galactose, glucose and uronic acid of the extruded orange pomace SDF accompanied by a decrease of most of the same sugars in the IDF fraction, implying a redistribution of IDF to SDF. Larrea et al. (2005a) proved that extrusion solubilized neutral pectic compounds or lateral linkages, whereas the main cellulose and rhamnogalacturonan linkages were not degraded. In fact, as depicted in Table 3, extrusion effectively increased the SDF content in many plant and vegetables by-products, leading to a reduction in their IDF content. Interestingly, in all cases, a reduction of no more than 6% in TDF was observed. The thermoplastic extrusion process may promote the formation of type 3 resistant starch by transglycosylation (Vasanthan et al. 2002), this is relevant when DFC are prepared from fruit by-products containing significant amounts of starch such as apple and orange pomaces (6.2 and 3.4 g·100 g⁻¹ dm, respectively (O'Shea et al. 2015)). Nevertheless, the increment in the IDF content produced by resistant starch is low.

Extrusion also modifies functional properties of DFC (Table 4). Huang and Ma (2016) observed an increase of 16, 85, 10, and 31% of the WHC, SC, WSI, and BD, respectively,

and a reduction of 32% in OHC in DFC obtained from extruded sweet orange pomace processed at 125 °C, 14% moisture, and 290 rpm. Significant increases in WSI and WHC (44, and 144%, respectively) were also observed by Larrea et al. (2005b) in extruded orange pulp DFC. Finally, the application of extruded modified DFC in food formulations not only enhanced functionality but also improved the sensorial quality of products. These researchers observed that the addition of 15% of extruded DFC from orange pulp in biscuits resulted in a higher sensory acceptability in terms of texture and flavor when compared to the control.

Thermal Treatments Thermal treatments are widely utilized to modify DFC composition and functionality. Although some treatments, such as blanching or scalding, are used as part of the DFC preparation (as mentioned in section 3), the modification on the DF composition by these treatments is notable. There are diverse changes produced by temperature in most of the carbohydrates associated to both SDF and TDF; therefore, the results on the DF composition produced by thermal treatments are not consistent in the literature, as depicted in Table 3. Benitez et al. (2011) and Tejada-Ortigoza et al. (2017b) observed a reduction in IDF accompanied by an increment in the soluble fraction in autoclaved onion bagasse and heat-treated DFC orange peels, respectively. Opposite results were reported by Marín et al. (2007), who showed a reduction of 54 and 26% in the SDF of sour orange and lemon pulp pomaces DFC, respectively, and an increment of up to 33% in the IDF fractions when treating with boiling water for 1 min. On the other hand, a blanching treatment of 90 °C for 1 min in carrot peel DFC increased 84 and 40% the SDF and IDF contents (Chantaro et al. 2008) whereas a similar treatment for 5 min applied in DFC of lime pomace reduced both fractions (26 and 10%, respectively).

The thermal effects on DF fractions depend on the process conditions, as well as on the association of the DF polysaccharides with other cell wall components. Thermal processing may release DF compounds from the cell wall and solubilize labile components associated to the DF structure, such as oligosaccharides, arabinoxylans, beta glucans, and pectins. Likewise, heat treatments may also promote cleavage of glycosidic bonds through β -eliminative degradation of pectic polysaccharides, resulting in solubilization of formerly IDF (Guillon et al. 2000). High-temperature processing may convert the structural pectin, or protopectin, into soluble pectins by hydrolysis, thereby increasing the SDF. However, more severe treatments may result in degradation of soluble pectin (Esteban et al. 1998; Maté et al. 1998; Yen and Lin 1998). On the other hand, the reduction in the IDF content by thermal effect is attributed to the partial degradation of cellulose and hemicelluloses into simpler

carbohydrates (mainly glucose and xylose and galactose, respectively). Higher degradations are obtained with temperatures above 100 °C and microwave treatments (Rehman et al. 2003). Finally, the situation where SDF decreases followed by the concomitant increment in IDF may be explained by a concentration effect produced by the treatment (Marín et al. 2007).

Analogous to the thermal-based DF modifications, the effects of temperature on the functional properties are not consistent among the reviewed studies. Nevertheless, the use of high temperatures almost always modifies the DFC's functionality (Table 4) through composition modifications. Fuentes-Alventosa et al. (2009) proposed the use of thermally modified DFC as viscosity and texture modifiers in foods. The de-esterification produced by heat treatments, mainly on pectic polysaccharides, could not be directly related to the modifications of the functional properties; however, the degree of methyl esterification could be involved by modifying the DFC's pore volume (Femenia et al. 1999). In this regard, Benítez et al. (2011) observed a significant increment in the BD produced by sterilization (115 °C for 26–31 min) in different DFC obtained from onion by-products, and a decrease in WHC, OHC, and SC. Conversely, Chantaro et al. (2008) improved WHC and SC after blanching DFC of carrot peels at 90 °C for 1 min. They implied that the higher observed values were due to the increment of SDF, as well as to structural modifications of fiber components which enhanced water absorption of the DFC. Nonetheless, the lack of correlation between the modified DF composition and the functional properties of DFC indicates that the structural features have more influence on the fiber functionality than the SDF:IDF ratio (López et al. 1996).

High Hydrostatic Pressure The use of high hydrostatic pressure technology has been studied to modified functionality of several biopolymers, including proteins, phospholipids and other carbohydrates (Garcia-Amezquita et al. 2009, 2013), as well as to assist DF extraction processes (Tejada-Ortigoza et al. 2016). Therefore, the utilization of this technology is promising in the modification of DF composition in fruit and vegetable by-products. Pressurization of by-products should be applied before the drying DFC step in order to enhance the transmitting pressure through the water within the food matrix. As shown in Table 3, high pressure could be used to increase the SDF content, maintaining the TDF content almost unchanged. Mateos-Aparicio et al. (2010) increased the SDF content in okara (soy-bean milk manufacturing by-product) from 2.1 to 3.4 g·100 g⁻¹ dm after 15 min processing at 400 MPa and 30 °C. This augmented the SDF:TDF ratio from 4.6 to 7.7, and consequently also increased the SC, WHC and OHC values. Tejada-Ortigoza et al. (2017a) observed an increment in the SDF content of 15

and 59% in mango and orange peels, respectively (600 MPa, at 22 °C for 10 min) followed by a reduction in IDF of 16 and 8%, with an irrelevant decline in TDF of no more than 1.8 g·100 g⁻¹ dm. As shown in Table 4, pressurization decreased the OHC and SC and increased the BD in mango, orange and prickly pear peels. The authors explained that a porous matrix structure was produced by high pressure, which influenced other relevant functional properties such as the enhanced capacity to retain water. The hygroscopic properties of the DFC, studied through isotherm analyses of the pressurized samples, were also modified (Tejada-Ortigoza et al. 2017c).

Although the use of high hydrostatic pressure has been widely recognized as a non-thermal technology, processing with mild temperatures, ranging between 50 and 80 °C, may further improve fiber conversion and therefore reduce treatment times. Mateos-Aparicio et al. (2010) increased the SDF from 2.1 to 19.7 g·100 g⁻¹ dm in okara processed for 15 min at 400 MPa and 60 °C. However, this research group did not find remarkable differences in SC, WHC and OHC with the use of higher temperatures. Recently Tejada-Ortigoza et al. (2017b) observed an increment of ≈ 90% in SDF (from 7.2 to 13.9 g·100 g⁻¹ dm) in orange peel DFC with a reduction in IDF of only 16% when processing for 20 min at 600 MPa and 70 °C. However, no significant changes ($p < 0.05$) in the functional properties were observed. The higher and lower SDF and IDF, contents suggest a partial solubilization of the IDF which significantly increased with the temperature effect in combined treatments (Tejada-Ortigoza et al. 2017a). Nevertheless, the combined effect of high pressure and temperature could potentially increase the IDF fraction, and consequently the TDF by the transformation of polymers, mainly composed of galactose, uronic acids and arabinose. In this context, Wennberg and Nyman (2004) observed a significant increment of IDF and TDF followed by a slight reduction in SDF in two varieties of white cabbage processed at 500 MPa, 80 °C for 10 min.

Finally, there is scarce information about the use of other emerging and non-thermal technologies to modify DFC. The use of ultrasound and microwave irradiation has been predominantly used to increase yields in chemical DF assisted extractions, and no reports of their use to modify fiber composition or functionality of DFC were found. Ultrasound produces, via cavitation, the disruption of plant cell wall structures increasing the solvent access to all tissues whereas microwave releases polysaccharides from cell walls improving extraction yields (Viridiana Tejada-Ortigoza et al. 2016). Moreover, several studies have shown that ultrasound modifies pure polysaccharides, such as pectin, carrageenan, gums, and starches (Ogutu 2015). Accordingly, the potential use of ultrasound and microwave for DFC modification is evident and should be considered for future studies.

Food Applications

Food Ingredient

Currently, consumers prefer and demand natural supplements in food formulations, as well as foods with remarkable health benefits. By-products DFC, besides the well-known physiological effects of DF consumption, can be used as food ingredients to take advantage of their technological functionalities. Moreover, by-products DFC can be used at a relatively low cost in food formulations as low caloric bulking agents, partially replacing caloric ingredients such as fats, flours/starches or sugars. Another important property is the antioxidant capacity of the DFC. This property is given by the antioxidant compounds associated within the DF matrix. These antioxidants are minor components of the DFC, but they contribute significantly to health, and the stability of foods (Ayala-Zavala et al. 2011). DFC could be applied in diverse food formulations, such as in bakery, meat, dairy, snacks and pasta products, (Table 5). In general, studies on the incorporation of DFC in foods have shown a good sensory acceptability at mild concentrations, since high amounts of DFC produce darker foods with harder textures and unpleasant flavors. Crizel et al. (2014) formulated a lemon-flavor ice cream increasing the DF content with citrus pomace DFC. Chocolate muffins were successfully produced with cocoa by-product DFC by Martínez-Cervera et al. (2011). However, higher DFC concentrations resulted in bitter aftertaste. Therefore, further studies must be conducted to increase the applications of DFC in food products without negatively affecting organoleptic attributes.

Bakery Products The use of by-products DFC in bakery items is probably the most widely studied probably because DFC are easier to incorporate in doughs and batters compared to other products and as well as the consumer perception of bakery foods as high-caloric. In this context, several studies have been conducted. Al-Sayed and Ahmed (2013) used watermelon or sharlyn melon rinds DFC to substitute flour or fat in cakes. Their results showed that the use of 5% of DFC to substitute flour and 10% to substitute fat reduced the lipid oxidation and free fatty acids formation during storage due to the high antioxidant compounds of the DFC. DFC also retarded the staling of cakes, increased the cake volume and significantly decreased the caloric value of final products. Likewise, wheat flour and starch were substituted with up to 25% of mango peel (Ajila et al. 2008), potato peel (Dhingra et al. 2012), or extruded orange pulp (Larrea et al. 2005b) DFC to produce biscuits. Similar shape and texture were obtained with a 5% substitution. Staling and oil rancidity significantly reduced in cupcakes produced with composite flours containing 5–20% potato by-product DFC (Khalifa et al. 2015). Peach bagasse DFC was successfully used as a fat replacer

in muffins which had good sensory acceptance when used at a concentration of 4% (Grigelmo-Miguel et al. 2001).

Meat Products In these products, the IDF fraction is relevant since it can absorb oil within the food formulation. DFC with higher oil absorption increases the flavor retention and the product yield after cooking (less shrinkage) where product usually loss most of the fat (Raghavendra et al. 2006). An increase in yield, fat and moisture retention were obtained by Sánchez-Zapata et al. (2010) in pork burgers formulated with 5 to 15% of Tiger nut residue DFC. On the other hand, the antioxidant capacity of DFC may improve the stability of cured products reducing lipid oxidation, as well as decreasing the residual nitrite levels (Aleson-Carbonell et al. 2003; Fernández-López et al. 2008). Furthermore, the use of DFC enhances the nutritional value of frequently consumed high lipid content products, reducing the caloric value and increasing the DF intake. A review regarding the use of citrus by-products DFC in meat products was published by Fernández-López et al. (2004), where the effect of the application on processed meat quality, as well as the beneficial results obtained from the fiber enrichment are discussed.

Snacks and Pasta Products Snacks are considered one of the most important food products and widely spread in world markets especially in developed countries. Unfortunately, most snacks are categorized as high glycemic index foods due to their high content of rapid-digestible carbohydrates, mainly starch. Hence, the use of DFC is a potential option to produce healthier products (Brennan et al. 2008). Moreover, the high SDF content of fruit and vegetable by-products DFC could aid in the production of more acceptable extruded snacks compared to counterparts produced from cereal-based fibers, since some studies have proved that higher SDF:IDF ratios produced snacks with better expansion and texture (Pai et al. 2009). As depicted in Table 5, the use of diverse by-products DFC (from 2 to 20%) has shown good results. However, some quality attributes, such as texture, porosity, and bulk density, especially when applied at higher concentrations, must be investigated and reviewed for further studies. In this regard, the use of modified DFC (see section 4), should be considered. For their part, flour in pasta products has been successfully replaced, increasing the nutritional value of the product, and maintaining the cooking yield. Crizel et al. (2015) produced fettuccini supplemented with 2.5% of orange by-product DFC. The enriched pasta had similar sensory evaluation attributed compared to the control. Likewise, macaroni elaborated with 5% of mango peel DFC showed comparatively higher antioxidant properties, as well as good sensory acceptance (Ajila et al. 2010).

Dairy Products Similar to other products, dairy formulations may be supplemented with DFC as fat replacer. Crizel et al.

Table 5 Uses and applications of dietary fiber concentrates from fruit and vegetable by-products in foods formulations

Food application	Source	Used concentration	Effect	Reference
Bakery products				
Biscuits	Mango peel	5–20% of wheat four substitution	Products with a high content of dietary fiber, and polyphenols. Breaking strength increased, and good sensory acceptability up to 10%.	(Ajila et al. 2008)
Biscuits	Potato peel	5–15% of wheat flour substitution	Nutritional value (dietary fiber) improved. Shape characteristics similar to control. Breaking strength slightly increased. Good sensory acceptability up to 5%.	(Dhingra et al. 2012)
Biscuits	Extruded orange pulp	5–25% of wheat flour/starch substitution	Used as wheat flour/starch substitute. Improvement of nutritional value (dietary fiber). Physical characteristics similar to control up to 5%. Reduced significantly the caloric value. Good sensory acceptability up to 15%.	(Larrea et al. 2005b)
Chocolate muffins	Cocoa	25–75% of oil substitution	Used as a fat replacer. Reduced the caloric value. Tender and crumbly texture was obtained. Reduced storage hardening.	(Martínez-Cervera et al. 2011)
Cookies	Watermelon rinds	10–30% of wheat flour substitution	Improved nutritional value (dietary fiber content and antioxidant activity). Significant reduction in the glycemic index. Good sensory acceptability. Products slightly softer than control but with lower spread ratio	(Naknaen et al. 2016)
Cupcakes	Potato by-product	5–20% of wheat flour substitution	Nutritional value (dietary fiber) improved. Reduced the caloric value. Increased the shelf-life stability, reduced oil rancidity and improved staling. Good sensory acceptability up to 15%.	(Khalifa et al. 2015)
Muffins	Peach bagasse	13.5–32.4% of sunflower oil substitution	Used as a fat replacer. Nutritional value (dietary fiber) improved. Reduced significantly the caloric value. Hardness increased. Acceptable sensory evaluation up to 4%.	(Grigelmo-Miguel et al. 2001)
Meat products				
Bologna sausages	Citrus pomace	0.5–2 g with 100 g meat	Nutritional value (dietary fiber) improved. Hardness lightly increased. Satisfactory sensory evaluation up to 1.5%. Shelf-life similar to control product.	(Fernández-Ginés et al. 2003)
Dry-cured sausages	Lemon peel (albedo)	2.5–10 g with 100 g meat	Nutritional value (dietary fiber) improved. Decreased residual nitrite levels and reduced oxidation. Sensory evaluation similar to control from 2.5 to 7.5%.	(Aleson-Carbonell et al. 2003)
Pork burger	Tiger nut residue	5–15 g with 100 g meat	Nutritional value (dietary fiber) improved. Enhanced cooking characteristics (yield, fat and moisture retention). Good sensory acceptability up to 10%.	(Sánchez-Zapata et al. 2010)
“Salchichón” (Spanish dry fermented sausage)	Orange pomace	1–2 g with 100 g meat	Reduced residual nitrite level. Increased micrococcus growth. Good sensory acceptability up to 1%.	(Fernández-López et al. 2008)
Dairy products				
Fermented milk	Orange and lemon pomace	1% of final product	Enhanced starter bacterial growth and survival of the probiotics. Excellent sensory acceptability of both, orange and lemon fibers.	(Sendra et al. 2008)
Ice cream	Orange peel, seed, and pulp pomace	0.74–1.5% of final product	Used as fat replacer with sensory analysis of texture, odor, and color similar to full fat ice cream. Melting rate similar to control. Bitter flavor and aftertaste can be avoided when hydro-distillation pretreatment is applied	(Boff et al. 2013; Crizel et al. 2013, 2014)
Skim milk yogurt	Apple, banana and passion fruit peels	1% of final product	Nutritional value (high dietary fiber content) improved. Increased the content of short chain fatty acids (SCFA) and polyunsaturated fatty acids.	(Do Espírito Santo et al. 2012b)
Yogurt	Pineapple peel	1% of final product	Used as a prebiotic. Reduced fermentation time of milk by probiotics. Textural properties similar to yogurt with inulin.	(Sah et al. 2016)
Snack products				
Corn extrudates	Carrot pomace	5–15% of corn starch substitution	Improved the extrudate's surface. High expansion was obtained with 5% at low moisture feeding condition	(Kaisangsri et al. 2016)
Extruded snacks	Tomato pomace	2–12.7% of barley flour substitution	Similar hardness with control at high processing temperatures. Higher sensory acceptability than control.	(Alan et al. 2008)
Ready-to-eat extruded snacks	Blend of orange peel, grape seed, and tomato pomace	3–7% of final product	Increased bulk density and water solubility of the extruded snacks, but decreased solubility and bulk density. Good expansion and sensory acceptability.	(Yağcı and Gögüş 2008)
Ready-to-eat extruded snacks	Cauliflower by-products	5–20% of wheat flour	Improved nutritional value, water absorption index increased with little effect on the snack hardness	(Stojceska et al. 2008)
Snack bars	Apple pomace			

Table 5 (continued)

Food application	Source	Used concentration	Effect	Reference
Supercritical flow extruded foods	Apple pomace	2.7% of oat substitution	Used to replace rolled oats. The texture was not adversely affected. Nutritional value (dietary fiber and phenolic compounds) improved.	(Sun-Waterhouse et al. 2010)
Wheat-corn based extrudates	Orange pulp bagasse	22% of final product	Light in weight products with density, hardness, and crispiness similar to starch extrudate.	(Paraman et al. 2015)
Pasta products		2.5–10% of sugar substitution	Enhanced expansion ratio and decreased the bulk density. Increased the force required to fracture the extrudate but decreased the cell wall.	(Pitts et al. 2016)
Fettuccini	Orange peel, seed and pulp pomace	2.5–7.5% of wheat flour substitution	Improved nutritional value (dietary fiber content and antioxidant capacity). Sensory evaluation similar to control at 2.5% fiber concentration.	(Crizel et al. 2015)
Macaroni	Mango peel	2.5–7.5% of semolina substitution	Improved nutritional value (dietary fiber and polyphenols and carotenoids). Improved antioxidant properties. Good sensory acceptability up to 5%.	(Ajila et al. 2010)

(2013, 2014) produced ice creams with up to 1.5% of orange by-products DFC, which showed similar sensory properties compared to the conventional product, as well as comparable physic properties, such as melting and texture. The high DF content in DFC makes them an excellent choice to promote fermentation in dairy products or even as prebiotics (see the following section); furthermore, the utilization of DFC with this purpose at concentration lower than 1% on fermented products is recommended. Higher concentrations significantly reduced color and flavor, and produced an undesirable bitter aftertaste. Addition of 0.6% of citrus by-product DFC improved the rheological properties of pasteurized milk-based yogurt, and enhanced the growth of *L. acidophilus* and *L. casei* (Sendra et al. 2010, 2008). Likewise, Do Espírito Santo et al. (2012b) increased the content of SCFA and polyunsaturated fatty acids with 1% of apple, banana or passion fruit peels DFC. Passion fruit fiber increased the production of conjugated linoleic acid, whereas the banana counterpart highly increased α -linolenic acid suggesting that fibers may be combined to enhance their functional benefits.

Prebiotic Functionality

Prebiotics are non- or low-digestible food ingredients which are selectively fermented by the gut microbiota, conferring health benefits to the host (Singh et al. 2015; Vitali et al. 2010). Regularly, all the considered prebiotics are associated to the DF; however, not all the dietary fibers exhibit prebiotic effects (Slavin 2013). There are some criteria to consider a food ingredient as prebiotic: 1. Resistance to gastric-acid or enzymatic hydrolyses, and gastrointestinal absorption, 2. Capable of being fermented by the intestinal microbiota, and 3. selectively enhance the growth and activity of specific bacteria associated with health benefits (G R Gibson and Roberfroid 2004). The high DF content of DFC, as well as the varied chemical composition of plant-origin by-products, could potentially comply with the mentioned conditions. In fact, fruit and vegetable by-products are rich in non-digestible oligosaccharides, which consumption are known to increase the *Bifidobacteria* population in the gut, regulate and decrease body weight, and increase the glucose tolerance (Kaczmarczyk et al. 2012). Nevertheless, there are scarce studies related to the prebiotic activity of fruit and vegetable by-products, and most of them had been conducted with DF extractions or pure polysaccharides. In vitro evaluation of the prebiotic activity of inulin-type carbohydrates from Jerusalem artichoke was studied by Rubel et al. (2014). A similar studied was conducted by Mandalari et al. (2007) using pectic carbohydrates extracted from bergamot peel. Gomez et al. (2010) studied the bacterial growing and SCFA production of fructans extracted from agave by in vitro fecal fermentation. However, only five studies dealing with the prebiotic potential of DFC were found (Table 6) and they do not completely

Table 6 Probiotic potential of dietary fiber concentrates from fruit and vegetable by-products

Source	DFC application	Experiment type	Prebiotic potential tests				Reference
			Fermentability	Microbial growth quantification	Gas production	SCFA production	
Tiger nut liquid by-product	Carbon source in culture media	In vitro - Microbiological	●		●		Sánchez-Zapata et al., 2013
Carrot, cocoa and pea fibers	Fiber source in diet	In vivo - Animal model	●			●	Roland 1995
Cactus pear and pineapple peel	Carbon source in culture media	In vitro - Microbiological	●		●		Díaz-Vela 2013
Coffee skin	Carbon source in culture media	In vitro - Fecal inoculation		●		●	Borrelli 2004, Jiménez-Zamora 2015
Almond skin	Fiber source in diet	In vivo - Human model		●			Liu 2014

Black dots show the test conducted in each study to evaluate the prebiotic potential of the DFC

proved their prebiotic capacity. Sánchez-Zapata et al. (2013) evaluated the use of tiger nut by-product DFC, from “horchata” industry, as carbon source for probiotic bacteria growth. Their results showed that this product promoted the growth of *Lactobacillus acidophilus* and *Bifidobacterium animalis* and also increased the SCFA production in inoculated MRS broth. A similar study was conducted by Díaz-Vela et al. (2013), who utilized DFC from prickly pear and pineapple peel. They observed a higher prebiotic activity score of both DFC for *Pediococcus pentosaceus* than for *Lactobacillus rhamnosus*, and *Aerococcus viridians*. A fecal fermentation using coffee skin DFC as carbon source was evaluated by Jiménez-Zamora et al. (2015). The DFC increased the population of *Bifidobacterium* spp. and decreased that of *Lactobacillus* spp. An in vivo study conducted in humans was performed by Liu et al. (2014) using almond skin DFC as dietary fiber source. They improved the intestinal microbiota profile and modified the bacterial activities. Nonetheless, further in vitro and in vivo studies must be conducted to demonstrate the prebiotic potential of these DFC.

Conclusions

Considerable attention has recently focussed on the obtaining of fiber-rich ingredients from fruit and vegetables by-products essentially due to the high content of TDF and SDF. A promising fiber-rich ingredient are DFC, which are prepared mainly by the dehydration and milling of fruit and vegetable by-products. These DFC have demonstrated to have a great physiological functionality and not only because of their DF content, but due to other health beneficial compounds, such as antioxidants. Despite DFC are not pure DF extracts, and contain high amount of other nutrients, such as lipids, proteins, digestible carbohydrates and minerals, DF is the essential component, which confers attractive technological functionality with enormous potential uses for formulating novel food products. Some technologies, like thermal and non-thermal treatments, have been studied to improve or enhance the DFC functionality. In this regard, extrusion have shown to produce greater modifications on the DF composition and functionality of DFC. The use of DFC as a technological, nutritional or prebiotic ingredient is already a market reality that must be improved to enhance both the applicability and the quality of DFC-based products.

Acknowledgements Authors García-Amezquita and Tejada-Ortigoza acknowledge the support from Tecnológico de Monterrey (Research Chair Funds GEE 1A01001 and CDB081) and the Mexican National Council of Science and Technology (CONACyT) Scholarship Program (Grant Nos. 260692 and 205265). This work was supported by CONACyT, through project number CB-2014-01-237271.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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