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Antioxidant Dietary Fibres: Potential Functional Food Ingredients from Plant Processing By-Products

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Abstract

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The number of dietary fibre enriched food products introduced to the food market has been increased due to several beneficial effects of dietary fibres, mainly on the digestive system. In recent years, there has been a trend towards finding new sources of dietary fibre, such as agronomic by-products. Dietary fibres produced from by-products of antioxidant rich foodstuffs comprise important and healthy antioxidants such as polyphenols and carotenoids. This brings along the antioxidant dietary fibre (ADF) concept, which combines beneficial effects of both dietary fibres and antioxidants. This review focuses on the present knowledge in the literature about the sources and potential applications of ADFs as functional ingredients in the food industry. Also it is aimed to attract the attention of producers to the economic importance of converting those food processing by-products into healthy value-added products.

Keywords: antioxidant; dietary fibre; plant waste; polyphenols; bioavailability

Dietary fibre is defined by the Codex Alimentarius Commission as the carbohydrate polymers with ten or more monomeric units which are not hydrolysed by the endogenous enzymes in the small intestine of humans and belong to the following categories: (1) edible carbohydrate polymers naturally occurring in the food as consumed; (2) carbohydrate polymers, obtained from food raw material by physical, enzymatic, or chemical means; (3) synthetic carbohydrate polymers. Similarly, the European Food Safety Authority (EFSA) described dietary fibre as non-digestible carbohydrates plus lignin, including all carbohydrate components occurring in foods that are not digestible in the human small intestine and pass into the large intestine (Jones 2014). They are believed to play an important role in maintaining the functional integrity of the gastrointestinal tract. High dietary fibre intake, depending on the dietary fibre consumed, is associated with body weight control and reduced risk of diseases such as colon cancer and atherosclerosis. An intake of 25–30 g dietary fibre per day is recommended by the American Heart Association (Pérez-Jiménez *et al.* 2008).

Nowadays, there is a trend to find new sources of dietary fibre that can be used as ingredients in the food industry (Rodríguez *et al.* 2006; Redondo-Cuenca *et al.* 2008). The most commonly consumed dietary fibre products are those derived from cereals. On the other hand, over the past decade high dietary fibre materials from fruits (citrus, apple, etc.) have been continuously introduced in the western world markets. In general, fruit dietary fibre concentrates have better nutritional quality than those found in cereals, because of their significant contents of associated bioactive compounds (flavonoids, carotenoids, etc.) (Vergara-Valencia *et al.* 2007; Fernandez-Lopez *et al.* 2009).

Antioxidants are compounds that inhibit or delay the oxidation of other molecules by inhibiting the initiation or propagation of oxidizing chain reactions (Velioglu *et al.* 1998). In recent years studies have shown the possible health risks related to the consumption of synthetic antioxidants (Vandghanooni *et al.* 2013; Panicker *et al.* 2014) and strict regulations now control their use in foods. Therefore, attention has been directed towards the develop-

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ment/isolation of natural antioxidants (Konczak *et al.* 2010).

Foodstuffs rich in dietary fibre and dietary fibre ingredients are popular in the food market, but their antioxidant capacities are negligible (Zhu *et al.* 2010). Recently, the concept of antioxidant dietary fibre (ADF) has been introduced (Saura-Calixto 1998). The main characteristic of these natural products is that they combine the physiological effects of both dietary fibre and antioxidants in a single material. One gram of ADF should have DPPH (2,2-diphenyl-1-picrylhydrazyl) free radical scavenging capacity equivalent to at least 50 mg vitamin E and dietary fibre content higher than 50% dry matter (DM) from the natural constituents of the material (Saura-Calixto 1998).

In this review, the existing knowledge in the literature about the sources and the potential applications of ADFs as potential functional ingredients in the food industry is examined.

Sources of ADF

Fruit and vegetable wastes from industrial food processing are usually discarded or used as animal feed and fertilizers. However, studies indicated that these so-called wastes of nutritive plant originated foods are rich in ADF. This key fact evoked the idea of utilising them as technological ingredients and/or food supplements. Extracts and/or powders of some by-products such as grape seed, cabbage leaves, etc. are also available on the shelves in drugstores as food supplements.

Researches carried out on the current topic by many researchers are summarised in Table 1 and applications of some of these sources as technological ingredients are summarised in Table 2. Results from these cited studies do not always present complete compatibility with the definition of ADF. However, since the antioxidant capacity and dietary fibre content of the studied material are high, they can be referred to as "good sources of ADF", therefore, they were included in this review.

Açaí. It is a tropical palm tree that occurs naturally in the Amazon region, which is also known as cabbage palm (Rufino *et al.* 2011). Fruits of açaí are proved to have a high antioxidant capacity (Rufino *et al.* 2011) and are therefore related to several positive health effects. A study on *Euterpe oleracea* species by Rufino *et al.* (2011) indicated that the açaí fruit pulp has dietary fibre content as high as 71.22 g/100 g dry mass (DM) in addition to its significant antioxidant capacity (20.73–1514.46 μmol Trolox/g DM) due to its polyphenols (1.50 g/100 g DM). It was stated that most of the polyphenol content of pulp (15.4 mg/g DM) could be associated with dietary fibre, which makes the açaí a good source of ADF (Rufino *et al.* 2011).

Apple. Apple possesses an antioxidant activity (Lim & Rabeta 2013; Li *et al.* 2014) mainly due to phenolic acids and flavonols. In addition, protocatechuic acid, chlorogenic acid, hyperoside, an unidentified phenolic acid, and a quercetin derivative are related to its high antioxidant capacity (Plaza *et al.* 2014). The apple peel is reported to have a higher antioxidant capacity than the pulp (Li *et al.* 2014).

A study on proximate analysis of three apple species by Lim and Rabeta (2013) showed that 83.28–89.92% of apple consists of water while the amount of dietary fibre is only 0.86–1.81%. However, the apple pomace separated during processing is reported to have 51.10 g/100 g DM of total dietary fibre, of which 14.60 g/100 g DM is soluble and 36.50 g/100 g DM is insoluble dietary fibre besides the total phenol content of 10.16 mg/g (Sudha *et al.* 2007) (Table 1). Yet, these contents depend on pressing, use of enzymes and additional extraction with water etc.

Cabbage. Species of cabbage (*Brassica oleracea*) are widely used in traditional medicine due to their anti-inflammatory and antibacterial properties (Samec *et al.* 2011). The antioxidant capacity of cabbage species has also been reported (Nilnakara *et al.* 2009).

Nilnakara *et al.* (2009) and Tanongkankit *et al.* (2010) studied the production of ADF powder from cabbage (*B. olera*cea L. var. *capitata*) outer leaves, which are usually separated as processing waste and are used only as fertilisers. In the study of Nilnakara *et al.* (2009) the crude fibre content of cabbage leaves was found to be 19.92–47.47 g/100 g DM, which was similar to the results (total dietary fibre 40.89 g/100 g DM) obtained by Tanongkankit *et al.* (2010). In addition, the total antioxidant capacity was reported to be 89.57–96.00% with the total phenolic content up to 571.50 mg GAE/100 g DM (Nilnakara *et al.* 2009). The authors also investigated the effects of heat treatments and slicing steps during powder production on dietary fibre content and antioxidant capacity of cabbage outer leaves at different steps, which indicated that these by-products are good sources of ADF.

Cactus. *Opuntia ficus-indica* (cactus pear) is a cactus that is well adapted to extreme climate and edaphic conditions, and it is mostly available in

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central Mexico. The cactus stem (cladode) is used in salads and the fruit is consumed as fresh fruit. Around 20% of fresh weight of cladodes and 45% of fresh weight of fruits are separated as by-products. By-products from Milpa Alta and Atlixco variety cladodes and Alfajayucan (green tuna) and Pelon Rojo (red tuna) fruits were found to be rich in ADF with 3.75 and 4.01 g/100 g edible fresh weight of dietary fibre content and up to 57.55 and 66.33 μmol Trolox equivalents/g DM of total antioxidant capacity for the cladodes and fruits, respectively (Bensadón *et al.* 2010). Ayadi *et al.* (2009) found that dietary fibre makes up 41.83–41.25% of total carbohydrates, whereas extractable polyphenols were reported to be 1.54–3.71 g GAE/100 g DM (Table 1).

Carrot. Carrot is well known for its high carotenoid content, particularly β-carotene. However, its antioxidant properties are not limited to carotenoids. Although levels are dependent on the species and the year of production, high amounts of phenolics, flavonoids and vitamins have been reported (Chantaro *et al.* 2008).

Carrot is widely used in the food industry, but its peels or pomace are discarded or used as an animal feed. Chantaro *et al.* (2008) studied carrot peels and found that these by-products contain 45.45 g/100 g DM of dietary fibre with a high antioxidant capacity (94.67%) (Table 1), which is suitable for the production of ADF powder. Their findings indicated that blanching improves the total dietary fibre (TDF) yield and the insoluble dietary fibre (IDF) to soluble dietary fibre (SDF) ratio while having no significant effect on total phenolic content (Table 2).

Cocoa beans. Cocoa, the main ingredient of chocolate, is rich in antioxidants, mainly flavonoids (Nehling 2012). Food products prepared with cocoa powder were reported to have high antioxidant activity, total polyphenols, flavanol monomers, and procyanidin oligomers (Stahl *et al.* 2009).

Lecumberri *et al.* (2007) studied a fibre-rich cocoa product and found that this product is not only rich in antioxidants but also is suitable to use as an ingredient to enrich low-calorie foods with dietary fibre (Table 1). The total dietary fibre content of this product was reported to be 60.51% DM, of which 10.09% was soluble. In addition, the antioxidant activity was found to be as high as 72.32 μmol Trolox eq./g DM with a total phenol content of 1.32% DM (Lecumberri *et al.* 2007).

Coffee beans. Coffee bean contains high levels of phenolic antioxidants such as hydroxycinnamic acid, and caffeine, which also possesses antioxidant properties (Ishizaka *et al.* 2013). Several benefits – either health benefits or technological benefits – of extracts of coffee bean or its by-products are reported mainly resulting from its high antioxidant capacity.

A study on coffee bean by-products by Murthy and Naidu (2012) indicated that coffee pulp, husk, silver skin, and spent coffee are rich in natural antioxidant compounds associated with dietary fibre and therefore can be classified as good sources of ADF (Table 1). These by-products contained 28–80% of total dietary fibre and 1.53–2.12 mmol Trolox/100 g DM of antioxidant activity.

Guava. Guava (*Psidium guajava* L.) is a tropical fruit, widely consumed fresh and also in processed forms (beverages, syrup, ice cream, and jams) (Jimenez-Escrig *et al.* 2001). Positive health effects of fruit and by-products of guava due to their high antioxidant capacity are reported. Studies by Jimenez-Escrig *et al.* (2001) and Martínez *et al.* (2012) confirmed this suggestion as guava concentrate and by-products exhibited high dietary fibre content (up to 69.1 g/100 g DM), antioxidant activity (up to 462 μmol Trolox eq./g DM) and associated polyphenols (26.2–77.9 g GAE/kg DM), which indicated that guava is rich in ADF (Table 1).

Grape. Grapes are cultivated mainly as *Vitis vinifera* for wine production. It is estimated that around 13% of the total weight of grapes used for wine making results in grape pomace, which is a by-product in this process (Torres *et al.* 2002). Grape pomace consists of seeds, skins and stems, and in some cases this by-product is used to extract grape seed oil.

Sauro-Calixto (1998) was the first to make a definition of ADF after his work on red grape peels. His study showed that grape pomace has 64.6% DM of dietary fibre with 400 mg DL-α-tocopherol/g lipid oxidation inhibition and 100 mg DL-α-tocopherol/g free radical scavenging capacity. The studies by Sanchez-Alonso *et al.* (2007) for grape and Llobera and Canellas (2007) for red grape yielded even higher results for dietary fibre content about 74–77.2% DM. A similar research by Llobera and Canellas (2008) indicated that white grape pomace and stem with total dietary fibre content of 715.6–790.5 g/kg DM and total extractable polyphenol content of 34.9–87.3 g GAE/kg DM could also be considered as ADF (Table 1).

Mango. Mango (*Mangifera indica* L.) is a popular fruit that can be cultivated in various regions, mainly in the tropics (Sultana *et al.* 2012). Although levels are dependent on cultivars, mango is generally rich

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Table 1. *In vitro* studies on antioxidant dietary fibers (ADFs)

ADF	Properties				Reference
	dietary fiber (DF)	antioxidant capacity	phenolics	others	
Açaí fruit pulp (*Euterpe oleraceae*)	TDF: 71.22 g/100 g DM	FRAP: 109.87–128.44 µmol Trolox/g DM ORAC: 379.97–1514.46 µmol Trolox/g DM ABTS: 20.73–55.79 µmol Trolox/g DM DPPH: 4.92–10.20 EC_{50}, g DM/g DPPH	Extractable polyphenols: 1.50 g/100 g DM Extractable polyphenols associated with DF: 11.2 (SDF) + 4.2 (IDF) mg/g DM	Hydrolyzable tannins: 1.59 g/100 g DM Condensed tannins: 1.24 g/100 g DM	Rufino *et al.* (2011)
Apple pomace	TDF: 51.10 g/100 g DM SDF: 14.60 g/100 g DM IDF: 36.50 g/100 g DM		Total phenol content: 10.16 mg/g		Sudha *et al.* (2007)
Cabbage outer leaves (*Brassica oleracea*)	Crude fiber: 19.92–47.47 g/100 g DM	Total antioxidant capacity: 89.57–96.00%	Total phenolic content: 44.35–571.50 mg GAE/100 g DM	Vitamin C: 75.06–532.85 mg/100 g DM	Nilnakara *et al.* (2009)
	TDF: 40.89 g/100 g DMSDF: 7.35 g/100 g DM IDF: 33.54 g/100 g DM		Total phenolic content: 496.92–739.24 mg GAE/100 g DM	Vitamin C: 432.89–639.55 mg/100 g DM β-carotene: 9.33–9.45 mg/100 g DM α-tocopherol: 5.36–5.45 mg/100 g DM	Tanong-kankit *et al.* (2010)
Cactus pear spiny and spineless cladodes (*Opuntia ficusindica*)	TDF: 41.83–51.24% of total carbohydrates		Total phenol: 825.81–975.82 mg/100 g DM	Total chlorophylle: 131.08–151.78 mg/100 g DM Chlorophyll *a*: 73.63– 82.59 mg/100 g DM Chlorophyll *b*: 35.34–39.84 mg/100 g DM β-Carotene: 0.649–1.01 mg/100 g DM	Ayadi *et al.* (2009)
Cactus pear stems and fruits (*Opuntia ficusindica*)	TDF: 3.75–4.01 g/100 g edible FW SDF: 7.98–9.8 g/100 g DM IDF: 19.39–54.45 g/100 g DM	FRAP: 40.39–65.33 µmol Trolox eq./g DM ABTS: 52.37–66.33 µmol Trolox eq./g DM	Extractable polyphenols: 1.54–3.71 g GAE/100 g DM	Carotenoids: 15.16–22.84 mg β-Carotene eq./g DM	Bensadón *et al.* (2010)
Carrot peel (*Daucus carota*)	TDF: 45.45 g/100 g DM	Total antioxidant capacity: 94.67%	Total phenolic content: 1371 mg GAE/100 g	β-Carotene: 20.45 mg/100 g DM	Chantaro *et al.* (2008)
Cocoa (fiber-rich cocoa product)	TDF: 60.51% DM SDF: 10.09% DM IDF: 50.42% DM	FRAP: 72.32 µmol Trolox eq./g DM TEAC: 7.73 µmol Trolox eq./g DM	Soluble phenols: As total phenols: 1.32 % DM As soluble tannins: 1.04 % DM	Condensed tannins: 4.46% DM	Leccumberi *et al.* (2007)
Coffee pulp, husk, silver skin, and spent coffee	TDF: 28–80 % SDF: 16–35% IDF: 8–64%	Total antioxidant activity: 1.53–2.12 mmol Trolox/100 g DM	Total polyphenols: 1.02–1.48 g GAE/g DM	Chlorogenic acid content: 2.3–3.0%	Murthy & Naidu (2012)

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Guava fiber concentrate	TDF: 69.1 g/100 g DM SDF: 11.1 g/100 g DM IDF: 57.7 g/100 g DM	ABTS: 1.9–20.9 μmol Trolox eq./g DPPH: 3.3–15.4 μmol Trolox eq./g FRAP: 6.0–11.1 μmol Trolox eq./g	Total extractable polyphenols: 39 mg GAE/100 g		Martínez *et al.* (2012)
Guava peel/pulp (*Psidium guajava* L. *Psidium acutangulum* L.)	TDF: 40.86–49.42% DM	DPPH: 1.92–3.72 EC_{50}, g DM/g DPPH FRAP: 233–462 μmol Trolox eq./g DM LDL:1.65-8.50 CLT_{50}, μg DM/ml	Total extractable polyphenols: 26.2–77.9 g GAE/kg DM	Condensed tannins: 1.06–2.87% DM	Jimenez-Escrig *et al.* (2001)
Mango fiber concentrate	TDF: 70.0 g/100 g DM SDF: 28.2 g/100 g DM IDF: 41.5 g/100 g DM	ABTS: 15.3–38.0 μmol Trolox eq./g DPPH: 31.7–47.1 μmol Trolox eq./g FRAP: 13.7–19.1 μmol Trolox eq./g	Total extractable polyphenols: 283–546 mg GAE/100 g		Martínez *et al.* (2012)
Mango fruit	TDF: 28.05 g/100 g DM SDF: 14.25 g/100 g DM IDF: 13.80 g/100 g DM	Antiradical efficiency (AE): 15.03×10^{-3} $1/EC_{50}$ TEC_{50}	Extractable polyphenols: 16.14 mg GAE/g DM		Vergara-Valencia *et al.* (2007)
Mango peel powder (MPP)	TDF: 51.2% SDF: 19.0% IDF: 32.%	Free radical scavenging activity, IC_{50}: 79.6 μg MPP	Total polyphenols: 96.2 mg GAE/g MPP	Total carotenoids: 3092 μg/g MPP	Ajila *et al.* (2008, (2010)
Orange by-products (albedo, flavedo and pulp)	TDF: 71.62 g/100 g DM		Extractable polyphenols: 40.67 mg GAE/g DM		Fernandez-Lopez *et al.* (2009)
Passion fruit fiber concentrate	TDF: 81.5 g/100 g DM SDF: 35.5 g/100 g DM IDF: 46.0 g/100 g DM	ABTS: 2.1–5.5 μmol Trolox eq./g DPPH: 1.5–5.1 μmol Trolox eq./g FRAP: 4.6–6.9 μmol Trolox eq./g			Martínez *et al.* (2012)
Passion fruit co-products	TDF: 53.51–71.79 g/100 g DM SDF: 5.26–19.45 g/100 g DM IDF: 48.25–52.34 g/100 g DM		Total phenolic content: 0.64-4.31 mg GAE/g	Total flavonoid content: 2.07–13.63 mg RE/g	Lopez-Vargas *et al.*, (2013)
Pineapple fiber concentrate	TDF: 75.8 g/100 g DM SDF: 0.6 g/100 g DM IDF: 75.2 g/100 g DM	ABTS: 1.7–7.7 μmol Trolox eq./g DPPH: 1.7–4.8 μmol Trolox eq./g FRAP: 2.5–6.2 μmol Trolox eq./g	Total extractable polyphenols: 129 mg GAE/100 g		Martínez *et al.* (2012)
Red grape pomace (*Vitis vinifera*)	TDF: 64.6% DM	LOI: 400 mg DL-α-tocopherol/g DPPH: 100 mg DL-α-tocopherol/g	Total extractable polyphenols: 26.9% DM Total non-extractable polyphenols: 2.0% DM		Saura-Calixto (1998)

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Table 1 to be continued

ADF	Properties				Reference
	dietary fiber (DF)	antioxidant capacity	phenolics	others	
Red grape pomace and stem (*Vitis vinifera*)	TDF: 74.5–77.2% DM	DPPH: 0.46–1.41 EC_{50}, mg DM/mg DPPH	Total extractable polyphenols: 2.63–11.6 g GAE/100 g DM	Condensed tannins: 10.3–22.3% DM	Llobera & Canellas (2007)
Red wine grape pomace (*Vitis vinifera*)	TDF: 61.32% DM SDF: 1.44% DM IDF: 59.88% DM	Radical scavenge activity: 37.46 mg ascorbic acid eq./g DM 91.78 mg α-tocopherol eq./g DM	Total phenolic compounds: 67.74 mg GAE/g DM	Condensed tannins: 12.11% DM	Tseng & Zhao (2013)
Sharlyn melon peel powder	Crude fiber: 29.59 % FW		4-Hydroxybenzoic acid: 325.3 μg/g DM Vanillin: 199.2 μg/g DM Chlorogenic acid: 66.2 μg/g DM Coumaric acid: 80.8 μg/g DM		Al-Sayed & Ahmed (2013)
Tomato peel	TDF: 86.15% SDF: 14.33% IDF: 71.82%		Total phenolic compounds: 158.10 GAE mg/100 g		Navarro-Gonzalez *et al.* (2011)
Water melon rind powder	Crude fiber: 17.28% FW		4-Hydroxybenzoic acid: 958.3 μg/g DM Vanillin: 851.8 μg/g DM Chlorogenic acid: 196.3 μg/g DM Caffeic acid: 41.4 μg/g DM Syringic acid: 32.3 μg/g DM Coumaric acid: 8.8 μg/g DM Sinapinic acid: 137.6 μg/g DM P-anisic acid: 81.5 μg/g DM		Al-Sayed & Ahmed, (2013)
White grape stem and pomace (*Vitis vinifera*)	TDF: 715.6–790.5 g/kg DM SDF: 39.4–103.0 g/kg DM IDF: 612.6 –751.1 g/kg DM		Total extractable polyphenols: 34.9–87.3g GAE/ kg DM	Condensed tannins: 79.0–168.3 g/kg DM	Llobera & Canellas (2008)

TDF – total dietary fiber; SDF – soluble dietary fiber; IDF – insoluble dietary fiber; DM – dry mass; FW – fresh weight; ABTS – 2,2-azino-bis(3-ethylbenzo-thiazoline-6-sulfonic acid); CLT_{50} – concentration of antioxidant that increases the lag time to 50% greater than thatof the control; DPPH – 2,2-diphenyl-1-picrylhydrazyl; EC_{50} – concentration of antioxidant needed to reduce the original amount of radical by 50%; FRAP – ferric reducing antioxidant power; GAE – gallic acid equivalents; RE – Rutin equivalents; LDL – low-density lipoprotein; LOI – lipid oxidantion inhibition; ORAC – oxygen radical absorbance capacity; Trolox – 6-hydroxy-2,5,7,8-tetramethylchroman-2-carboxylic acid; TEC_{50} – time necessary to reach the steady state at EC_{50}; Phenolic glycosides-Q* – mixture of quercetin glycosides also include their methyl ethers; Phenolic glycosides-K* – mixture of kaempferol glycosides also include mono to triglycosides

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in β-carotene, L-ascorbic acid, total phenols and individual phenolic compounds (Liu *et al.* 2013). Its peels, leaves, stem bark and kernels were also found promising as functional food ingredients due to their high levels of antioxidants (Pitchaon 2011; Sultana *et al.* 2012).

It was shown that mango fruit (Vergara-Valencia *et al.* 2007), mango fibre concentrate (Martinez *et al.* 2012) and powder from mango peels (Ajila *et al.* 2008, 2010) also possessed high dietary fibre content (total dietary fibre 28.05–70.0 g/100 g DM) and polyphenols (16.14–283 mg GAE/100 g) (Table 1), which makes mango a good source of ADF.

Melon. Al-Sayed and Ahmed (2013) successfully showed that watermelon rinds and Sharlyn melon peels, which are usually discarded as wastes, are good sources of ADF with a crude fibre content of 17.28–29.59% (Table 1). The authors worked on fortification of cakes with powder produced from these by-products and found out that it is possible to evaluate water melon rinds and Sharlyn melon peels for enriching foods with functional components while providing better freshness to the product (Table 2).

Orange. Orange is well known for its high vitamin C and phenolic content. Orange juice is also rich in these bioactive compounds contributing effectively to its antioxidant activity (Stella *et al.* 2011).

A study by Escobedo-Avellaneda *et al.* (2014) shows that the flavedo contains higher vitamin C, flavone, and carotenoid content compared with orange juice while the albedo is rich in phenolics, flavanones, and antioxidant activity. Fernandez-Lopez *et al.* (2009) confirmed their results of high phenolics (40.67 mg GAE/g DM) and they also indicated that the orange peel has high dietary fibre content (71.62 g/100 g DM) (Table 1).

Passion fruit. According to Simirgiotis *et al.* (2013) the pulp and peel of banana passion fruit were shown to reveal high antioxidant activity with the latter having the highest flavonoids. A study by Martinez *et al.* (2012) indicated that dietary fibre concentrate from by-products of Passiflora contains 81.5 g/100 g DM of total dietary fibre with high antioxidant activity (1.5–6.9 μmol Trolox eq./g) related to dietary fibre. A similar study by Lopez-Vargas *et al.* (2013) on fibre from co-products of yellow passion fruit, pulp, seed, and albedo yielded 53.51–71.79 g/100 g DM of total dietary fibre with the total phenolic content of 0.64–4.31 mg GAE/g (Table 1).

Pineapple. Pineapple *(Ananas cosmosus)*, a member of the family *Bromeliaceae*, is a widely consumed tropical fruit which can be consumed as fresh fruit, juice, jam, jelly and dried product. A study by Upadhyay *et al.* (2012) showed that the pineapple stem, which is separated as waste, has moderate antioxidant and antimicrobial effects, while antifungal effect was considerable probably due to high benzoic acid content.

Martinez *et al.* (2012) studied pineapple fibre concentrate, obtained as waste from industrial productions and showed that pineapple fibre concentrate is rich in total dietary fibre (75.8 g/100 g DM) and shows high antioxidant activity (1.7–7.7 μmol Trolox eq./g).

Tomato. Tomato (*Solanum lycopersicum*) – a good source of the carotenoids lycopene and β-carotene, phenols, flavonoids, and ascorbic acid – is widely used in the food industry as well as its domestic use is important (Kavitha *et al.* 2014). Processes that tomato goes through during preparation have an effect on antioxidant capacity. Peeling was shown to cause serious losses in lycopene, β-carotene, ascorbic acid, and phenolic contents while seed removal resulted in a loss of carotenoids and phenolics which consequently cause a decrease in antioxidant capacity (Vinha *et al.* 2014).

Navarro-Gonzalez *et al.* (2011) reported that the tomato peel is rich in phenolics (158.10 GAE/100 g) with high dietary fibre content as high as 86.15% (Table 1).

ADF as a technological ingredient

Contribution to storage stability and quality. Since there is an increased interest in using natural ingredients in food production, *in vitro* and *in vivo* studies on ADFs suggest the use of ADF as a food ingredient to improve shelf life due to its inhibitory effect on lipid oxidation in food products besides increasing the nutritive value of the product. Grape antioxidant dietary fibre (GADF) has been studied the most frequently. With the addition of incremental amounts of GADF, storage behaviour of chicken hamburgers (Sayago-Ayerdi *et al.* 2009), fish mince (Sanchez-Alonso *et al.* 2007; Sanchez-Alonso & Borderias 2008), meagre sausages (Ribeiro *et al.* 2013), and yogurt and salad dressing (Tseng & Zhao 2013) were investigated. Likewise, the addition of Fucus ADF to minced horse mackerel (Diaz-Rubio *et al.* 2009) and Sharlyn melon peel and water melon rind powder to cake (Al-Sayed & Ahmed

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Table 2. Studies on antioxidant dietary fibers (ADFs) as technological ingredients

ADF	Product	Storage/Process	Properties	Reference
Apple pomace	Cake (Wheat flour + apple pomace blend)	fortification	Increase in water absorption. Increase in dough development time and decrease in dough stability. Increased resistance to extension. Increased pasting temperature. Decrease in peak viscosity, hot paste viscosity and cold paste viscosity. Decrease in cake volume and increase in density. Increase in hardness. Reduction in overall product acceptability. High acceptance in 20% pomace added samples	Sudha *et al.* (2007)
Cabbage outer leaves	Dietary fiber powder production	slicing, blanching, drying	Better total phenolic content, total antioxidant activity and vitamin C retention results in steam blanching than water blanching. Significant decrease in total antioxidant activity by both steam and water blanching and drying. Higher degradation in unblanched samples. No significant effect of preparation steps but reduction by drying on β-carotene and α-tocopherol content	Tanongkankit *et al.* (2010)
	Dietary fiber powder production	blanching, drying	Faster drying of blanched samples. Increase in crude fiber, protein and fat contents and decrease in ash and carbohydrate contents after blanching. Significant loss of TPC, TAA, and Vitamin C after blanching and drying. Acceleration of degradation by higher temperatures. Darker and greener color with slight loss of yellowness	Nilnakara *et al.* (2009)
Cactus pear spiny and spineless cladodes powder	Cake (Wheat flour + powder blend)	fortification	Increased ability of dough to retain gas. Increased extensibility and deformation energy. Decrease in volume and cohesion. Increase in hardness, adhesion, stickiness and density. Higher effect of Maillard and caramelisation reactions at 20% level. Poor product acceptability	Ayadi *et al.* (2009)
Carrot peel	Antioxidant high dietary fiber powder production	blanching, hot air drying	Improved TDF and IDF : SDF ratio by blanching. Enhanced water retention capacity and swelling capacity. Partial degradation of antioxidants during blanching and drying. No significant difference in total phenolic content, β-carotene and antioxidant capacity between blanched and unblanched samples	Chantaro *et al.* (2008)
Fucus (*Fucus vesiculosus*)	Minced fish muscle (Horse mackerel – *Trachurus trachurus*)	frozen storage (–20°C), 5 months	100–110% FRAP and 300–420% ABTS difference than control. No significant difference in water binding and water holding capacity. No significant difference in sensory quality for 1% ADF added samples while pleasant fresh-seafood flavor is reported for 2% ADF added samples	Diaz-Rubio *et al.* (2009)
Grape	Raw and cooked chicken hamburgers	refrigerated storage (4°C), 0, 3, 5, and 13 days	Increase in redness while reduction in lightness and yellowness. No effect in product acceptability. Resistance to lipid oxidation in 2% GADF added samples. Protection of RSC values in 1% GADF added samples while serious reduction in 2% GADF added samples. Retardation and inhibition of lipid oxidation during storage at all levels	Sayago-Ayerdi *et al.* (2009)
	Minced fish muscle (Horse mackerel – *Trachurus trachurus*)	frozen storage (–20°C), 6 months	Major changes in first 3 months. Up to 225% FRAP and DPPH effectiveness. Less formation of conjugated diene and triene hydroperoxides. Up to 57.28% lower TBA-i values. Up to 62.34% inhibition of oxidation	Sanchez-Alonso *et al.* (2007)
	Minced fish muscle (Horse mackerel – *Trachurus trachurus*)	frozen storage (–20°C), 6 months	No protection against protein aggregation. Increase in water retention proportional to amount of the fiber added. Reduction in thawing drip. Increase in cooking yield. Significant decrease in shear strength. Reduction in chewiness, hardness and cohesiveness. No clear influence in mechanical properties. Maximum product acceptability in 2% GADF added samples. Up to 69.4% inhibition of oxidation	Sanchez-Alonso & Borderias (2008)

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Table 2 to be continued

ADF	Product	Storage/Process	Properties	Reference
Grape	Meagre sausages	refrigerated storage (2 ± 2°C), 98 days	Higher exudation. Decrease in hardness and elasticity. Increase in darkness, redness and yellowness. Increase in acidity. Higher radical scavenging activity and reducing power. Lower TBAR values. Less product acceptability due to unpleasant odor and flavor. Acceptable microbiological quality throughout the storage time. Lower levels of H_2S producer counts	Ribeiro *et al.* (2013)
	Yogurt and salad dressing	refrigerated storage (4°C), 3 weeks	Decrease in lightness and hue and increase in chroma. Lower pH. No difference in syneresis except for significant increase in 3% wine grape pomace added samples. Reduction in viscosity. Higher lactic acid percentage. Lower peroxide values than control. Reduction of total phenolic content during storage. Less reduction of TPC in salad dressing due to lower pH. Higher radical scavenging activity values proportional to WGP addition. No significant effect on sensory analysis	Tseng & Zhao (2013)
Mango	Bakery products	fortification	Increased water holding capacity values with temperature. Lower oil holding capacity than other fiber concentrates. Higher SDF content. Slower starch digestion. Lower hydrolysis index (HI) and predicted glycemic index (pGI) values	Vergara-Valencia *et al.* (2007)
Mango peel powder (MPP)	Soft dough biscuits	fortification	Increase in water absorption. Increase in dough development time and mixing tolerance index. Decrease in dough stability. Decrease in thickness and diameter. Increase in hardness. Decrease in brightness and yellowness. Product acceptability up to 10% MPP incorporation. Slight bitter taste at 20% level	Ajila *et al.* (2008)
	Macaroni	fortification	Increase in firmness and cooking loss of cooked macaroni. Decrease in cooked weight. Yellow-yellowish brown colour. Acceptability at 5% level	Ajila *et al.* (20010)
Melon peel powder (Water melon rind & Sharlyn melon peel)	Cake	fortification/ storage (21 days)	Increase in weight (decrease at 5 and 7.5% levels), volume and density. Increase in darkness. Greenish colour in water melon rind powder added samples. Increase in yellowness in Sharlyn melon peel powder added samples. Less loss in moisture during storage. Better freshness in water melon rind powder added samples. Slower peroxide formation. No significant sensorial difference at 2.5% addition	Al-Sayed & Ahmed (2013)
Orange by-products	High dietary fiber powder (storage)	vacuum and air packaging (room temperature, 11 months)	Significant increase in moisture content in last 4 months. Significant increase in water activity during first 6 months. Colour changes due to increased moisture content. No significant differences between packaging type. Ideal storage conditions: 6 months, vacuum packaging	Fernandez-Lopez *et al.* (2009)

TPC – total phenolic content; TAA – total antioxidant activity; TDF – total dietary fiber; IDF – insoluble dietary fiber; SDF – soluble dietary fiber; RSC – radical scavenging capacity; FRAP – ferric reducing antioxidant power; DPPH – 2,2-diphenyl-1-picrylhydrazyl; GADF – grape antioxidant dietary fiber; TBA-i – thiobarbituric acid index; TBARS – thiobarbituric acid reactive species

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2013) were also examined. Lipid oxidation, microbial stability, sensorial quality and nutritional, textural, physical and mechanical properties of the products were investigated after the addition of ADFs to the products of interest.

All the studies (Table 2) on this topic agree that the addition of ADF can significantly prevent and/or retard lipid oxidation throughout storage due to the presence of antioxidants (Sanchez-Alonso *et al.* 2007; Sanchez-Alonso & Borderias 2008; Diaz-Rubio *et al.* 2009; Sayago-Ayerdi *et al.* 2009; Al-Sayed & Ahmed 2013; Ribeiro *et al.* 2013; Tseng & Zhao 2013).

A study by Sanchez-Alonso and Borderias (2008) on the addition of GADF to frozen minced fish muscle indicated higher water retention and cooking yield with a reduction in thawing drip proportional to the ratio of GADF added. According to Al-Sayed and Ahmed (2013) cakes substituted with melon peel powder lost less water and yielded better freshness during storage. On the contrary, Ribeiro *et al.* (2013) reported higher exudation in meagre sausages. Moreover, Tseng and Zhao (2013) reported an increase in synaeresis in yogurt samples added more than 3% wine grape pomace. Also a study by Diaz-Rubio *et al.* (2009) showed that the addition of Fucus ADF to fish mince did not cause a significant difference in retained water after thawing compared to the results obtained by Sanchez-Alonso and Borderias (2008), who added GADF to the same product. This information might show that properties like water retention, holding and binding capacities are likely to be dependent on the food product and the type of ADF added.

Mechanical and physical properties and texture of the product also seem to be affected by the addition of ADF. Colour is one of the factors affecting the acceptability of the product. Addition of GADF to chicken hamburgers (Sayago-Ayerdi *et al.* 2009) and meagre sausages (Ribeiro *et al.* 2013) increased redness. Addition of whole grape pomace to yogurt and salad dressing was reported to give higher redness and blueness values compared to results obtained by the addition of liquid pomace and freeze-dried pomace extracts (Tseng & Zhao 2013). Lightness was reported to be decreased by the addition of GADF to chicken hamburgers (Sayago-Ayerdi *et al.* 2009), meagre sausages (Ribeiro *et al.* 2013), yogurt and salad dressings (Tseng & Zhao 2013). Yellowness was reported to be decreased in chicken hamburgers (Sayago-Ayerdi *et al.* 2009) while it was increased in meagre sausages (Ribeiro *et al.* 2013). The changes in colours were associated with some factors such as the preparation steps the product passed through (Sayago-Ayerdi *et al.* 2009), the colour of added ADF (Ribeiro *et al.* 2013), or homogeneity of the mixture (Tseng & Zhao 2013).

By the addition of GADF, an increase in the acidity of the products (Ribeiro *et al.* 2013), reductions in shear stress, chewiness, hardness, and cohesiveness of minced fish muscle (Sanchez-Alonso & Borderias 2008) and viscosity of yogurt (Tseng & Zhao 2013) were also reported.

All these changes in the product are supposed to have an effect on organoleptic quality and product acceptability. However, although some panellists found unpleasant odour and flavour for the GADF added meagre sausages due to a sour impression (Ribeiro *et al.* 2013), most of the studies showed that ADF addition does not have a significant effect on product acceptability up to a certain level of inclusion (Diaz-Rubio *et al.* 2009; Sayago-Ayerdi *et al.* 2009; Al-Sayed & Ahmed 2013; Tseng & Zhao 2013).

Applications to bakery formulations and macaroni. Vergara-Valencia *et al.* (2007) replaced commercial wheat germs with mango dietary fibre concentrate (MDF) in cookies and bread, and observed that MDF increased the TDF levels of the products with a more balanced SDF/IDF ratio. They also reported that extractable polyphenols were not significantly affected during baking.

Sudha *et al.* (2007) concluded that ADFs increased water absorption in their study on cake samples added apple pomace. Their results showed that apple pomace can be a good source to enrich foodstuffs with dietary fibre and polyphenols as the cakes prepared with 25% apple pomace had 14.2% dietary fibre and 3.15 mg/g total phenol content. However, the authors stated that temperatures above 60°C might cause a loss of phenolics.

Ayadi *et al.* (2009) studied the addition of flour produced from cactus pear (*Opuntia fucus indica*) cladodes to cakes. Cladode flour had a natural green colour, like that of pistachio, which the authors suggested as an alternative colorant to synthetic colouring agents. The sensorial tests showed that samples with 5% cladodes flour had an acceptable sensorial quality.

Results from the study by Ajila *et al.* (2008) showed that MPP is useful to improve both dietary fibre and antioxidant properties of soft dough biscuits. MPP was also used to fortify macaroni preparations by Ajila *et al.* (2010) (Table 2).

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CONCLUSION

As there arise negative concerns regarding the use of synthetic ingredients for food preservation, natural alternatives such as plant extracts rich in phenolics are gaining popularity among consumers. ADF is proposed as a new potential antioxidant ingredient that was proved to prevent or delay lipid oxidation in foods, which is a major problem of the food industry. Besides, ADF brings along several benefits together; it gives an opportunity to enrich food formulas with both dietary fibre and antioxidants – which are essential parts of a healthy diet – at the same time while soothing concerns of the consumers. By-products from the processing of plant-originated food materials are good sources of ADF. Using these wastes as ingredients may provide environmental and economic benefits. However, sensorial properties must be considered, since the addition of ADF causes numerous changes in the product and sensorial tests indicate that products formulated with ADF are acceptable only to some extent.

Sources of ADF are not limited to those reviewed in this article. Future studies must be carried out on finding new sources and better methodologies to make better use of plant originated antioxidant and dietary fibre rich food material; namely ADF.

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