Food & Function

REVIEW

Cite this: *Food Funct.*, 2014, **5**, 1063

Dietary fiber and phenolic compounds as functional ingredients: interaction and possible effect after ingestion

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Received 30th January 2014
Accepted 15th March 2014

DOI: 10.1039/c4fo00073k

www.rsc.org/foodfunction

Dietary fiber and phenolic compounds are two recognized dietary factors responsible for potential effects on human health; therefore, they have been widely used to increase functionality of some foods. This paper focuses on showing the use of both substances as functional ingredients for enriching foods, and at the same time, describes the use of a single material that combines the properties of the two types of substances. The last part of the work describes some facts related to the interaction between dietary fiber and phenolic compounds, which could affect the bioaccessibility and absorption of phenolics in the gut. In this sense, the purpose of the present review is to compile and analyze evidence relating to the use of dietary fiber and phenolic compounds to enhance technological and nutritional properties of foods and hypothesize some of the possible effects in the gut after their ingestion.

Introduction

Dietary fiber and phenolic compounds are two plant food constituents that are associated with many health benefits and have been demonstrated to reduce risk for developing cancer and some chronic diseases.[1] Therefore, the intake and the use of these compounds as functional ingredients to enrich foods have been increasing in order to provide health benefits to consumers.[2,3] Dietary fiber has an essential role in intestinal health and appears to be significantly associated with a reduction of cholesterolaemia and modification of the glycaemic response.[4] Furthermore, phenolic compounds have potent antioxidant and free-radical scavenging properties that protect against oxidative damage to important biomolecules.[5] All these properties are associated with the chemical structures of these compounds, which determine their subsequent physiological and nutritional properties as functional ingredients.[6]

Dietary fiber and phenolic compounds are generally studied separately, probably because of differences in their chemical structures, physicochemical and biological properties, and metabolic pathways.[7] However, there is scientific evidence suggesting that indigestible components of dietary fiber (polysaccharides) can associate with other food constituents, such as phenolic compounds.[7,8] This interaction can occur during fruit ripening, food processing or during the gastrointestinal process and can be ascribed to the ability of polysaccharides to bind and trap phenolic compounds at several sites.[7] Therefore, dietary fibers with associated phenolic compounds have become increasingly interesting, as these could be useful for the food industry to enhance the bioactive and technological properties of products.

Some authors have identified dietary fiber with associated phenolic compounds with an exceptional biological antioxidant capacity from mango peels, unripe whole mango, pineapple shells, guava pulp, grape pomace and other vegetable materials.[9–12] This material promises an enhancement in functional properties of foods and at the same time an increase in the antioxidant capacity of the product with exceptional effects on human health.[13–17] However, the *in vivo* antioxidant activity of dietary fibers with associated phenolic compounds is still disputed, because the bioavailability of the antioxidants is no guarantee, due to evidence indicating that dietary fiber may negatively affect the release and absorption of some molecules, including phenolic compounds.[18]

In this context, the aim of this review is to analyze the use of dietary fiber and phenolic compounds as advantageous functional ingredients, as well as to describe the chemical interaction that can arise between these two components (fiber and phenolics), which can provide functionality to the food but may impact the bioactive effects of the compounds after their intake.

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Dietary fiber and phenolic compounds

Dietary fiber and phenolic compounds are two important plant constituents that are associated with multiple physiological effects; so their study, consumption and use as functional ingredients have widely increased.[19] According to AACC[20] and DeVries *et al.*,[21] dietary fiber is defined as "the remnants of the edible part of plants or analogous carbohydrates that are resistant to digestion and absorption in the human small intestine, with complete or partial fermentation in the large intestine". Non-starch polysaccharides are considered the main dietary fiber components, and they are classified by their solubility as insoluble (IDF) and soluble dietary fiber (SDF). IDF includes cellulose, hemicellulose or chitin; however, resistant starch is also consider a type of IDF, whereas the SDF class includes non-starch polysaccharides such as pectins, β-glucans, gums, mucilage, oligosaccharides or inulin.[22] Besides, other indigestible compounds can be considered as part of the dietary fiber structure, such as resistant protein, phenolic compounds, waxes, saponins, phytates, and phytosterols that exist in plant cell structures.[23] In fact, some works hypothesize that several bioactive benefits of dietary fiber are determined by the action of some linked compounds, such as phenolic compounds.[24,25]

High dietary fiber diets are associated with improvement in gastrointestinal health and reduction and treatment of some cardiovascular diseases and some forms of cancer.[26,27] Indeed, a reduction of hyperlipidemia, hypertension, modification of the glucose tolerance and insulin response and increased satiety, and hence some degree of weight management, are other physiological effects associated with dietary fiber consumption in humans.[4] Furthermore, dietary fiber is widely used to enrich foods, because it can impart some functional properties (*e.g.* increase water holding capacity, emulsification and/or gel formation, viscosity, adsorption/binding or fermentability).[6] In this sense, consumption of dietary fiber-rich foods, as well as the use of dietary fiber as a functional ingredient, has increased.

Phenolic compounds are other important bioactive compounds identified in plant foods and represent a wide variety of compounds characterized by a phenolic structure (aromatic ring bearing one or more hydroxyl groups).[28] They are present in all plant organs, having great significance in plant physiology and protecting plants against pathogens, parasites, predators and plagues.[29] Their structures are diverse and can be classified into different groups as a function of the number of phenol rings that they contain and the structural elements that bind these rings to one another.[30] Distinctions are thus made between phenolic acids, flavonoids, lignans, and stilbenes. In addition to this diversity, phenolic compounds may be associated with carbohydrates (simple and complex), lipids, organic acids, and as mentioned, some phenolic compounds can also be linked to cell wall components (cellulose, hemicelluloses, and lignin).[29]

The consumption of foods rich in phenolic compounds is associated with various physiological effects, such as preventing cancer and some chronic diseases, due to the compounds' potent antioxidant properties and free radical scavenging.[30] Thus, the consumption and incorporation of these molecules into foods have been increasing, in order to enhance health.[2] Phenolic compounds are ubiquitous in fruits, vegetables, cereals, nuts and furthermore in plant-based beverages, such as wine, beer and tea.[29] However, the biological properties and health effects of phenolic compounds depend on their respective intake and bioavailability, which can be affected by different factors including the binding of phenolic compounds within the food matrix, especially dietary fiber.[18,30–32] The maximum concentration in plasma rarely exceeds 1 μM after the consumption of 10–100 mg of a single phenolic compound. Nevertheless, the total plasma phenol concentration is probably higher due to the presence of metabolites formed in the body's tissues.[33]

Therefore, dietary fiber and phenolic compounds are two food constituents which present distinct functional properties. However, recent evidence suggests that the presence of phenolics–carbohydrates complexes in food is generally higher than that of simpler compounds, and these types of interactions have been underestimated in many papers mainly due to analytical problems.[34] Due to the importance and interest of different researchers to elucidate the biological role of these complexes, more studies are being developed. Regarding these molecules, Saura-Calixtro[32] established a new concept for polyphenols attached to macromolecules such as fiber, which is well described in the next section.

Dietary fiber with phenolic compounds associated: a new concept and a potential food ingredient

Nowadays, the dietary fiber concept, in which healthy effects were previously attributed only to non-starch polysaccharides and lignin components, is changing in order to consider food as a complex matrix capable of carrying other non-digestible food constituents that are resistant to digestion and absorption in the human small intestine, with complete or partial fermentation in the large intestine.[8,24,25] Phenolic compounds are the most abundant antioxidants in plant foods that can be found chemically associated with the fiber matrix (Fig. 1). In this sense, the concept of "antioxidant dietary fiber" has been recently introduced and was defined as a dietary fiber concentrate, containing significant amounts of natural antioxidants (mainly phenolic compounds) associated with non-digestible compounds.[32] This material combines the physiological properties of both dietary fiber and phenolic compounds and promises to be a potential food ingredient useful in enhancing the bioactive and technological properties of products (Fig. 2).

The most abundant phenolic compounds linked to dietary fiber belong to the chemical class of hydroxycinnamic acids. In fruits, these types of compounds are mainly polymeric tannins, and after hydrolysis the most common phenolic compounds are gallic and ellagic acids.[35] However, in cereals the main compound linked to fiber is ferulic acid, followed by diferulic acids, and then sinapic, *p*-coumaric and caffeic acids.[25] Through this conjunction, it is estimated that around 2.5% of the dietary

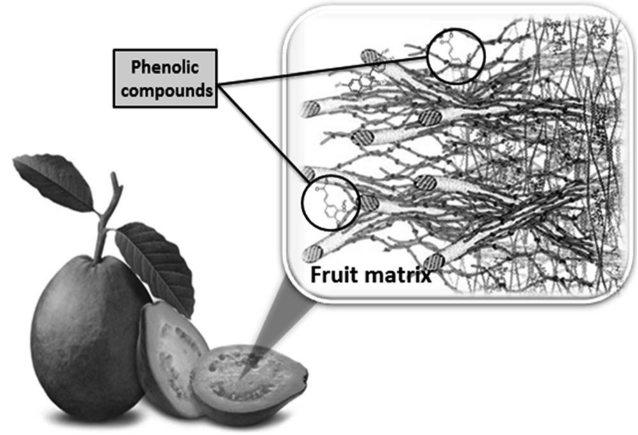

Fig. 1 Phenolic compounds linked to dietary fiber in fruit matrix.

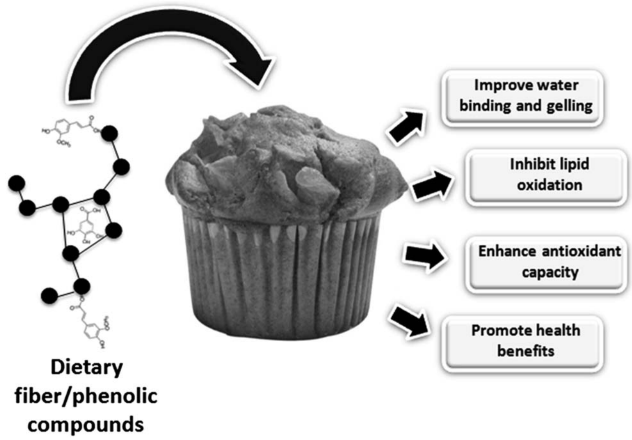

Fig. 2 Incorporation of dietary fiber with antioxidant activity into food to enhance its properties.

fiber content present in fruits is associated with phenolic compounds.[7] Indeed, 95% of grain phenolic compounds are linked to dietary fiber polysaccharides, mainly α-arabinoxylans, as diferulates covalently bound through ester bonds.[25]

There are certain requirements that the material should meet to be considered as an "antioxidant dietary fiber" and a potential food ingredient: (1) dietary fiber content should be higher than 50% on a dry matter basis. (2) One gram of "antioxidant dietary fiber" should have a capacity to inhibit lipid oxidation equivalent to at least 200 mg of vitamin E and a free radical scavenging capacity equivalent to at least 50 mg of vitamin E. (3) The antioxidant capacity must be an intrinsic property, derived from natural constituents of the material. In this context, it can be suggested that phenolic compounds could be dietary fiber constituents in some food matrices, and that these compounds could confer the antioxidant activity attributed to the dietary fiber as a beneficial effect. However, the physiological antioxidant effect of dietary fibers with associated phenolic compounds is still disputed, because the chemical interaction between these two molecules might prevent the release and absorption of phenolics.

Sources of dietary fiber with associated phenolic compounds

In order to take advantage of the properties of this new dietary fiber concept, some authors investigated plant food sources of dietary fiber with phenolic compounds associated. Table 1 shows the difference in total dietary fiber and phenolic compounds content from different whole fruits, byproducts and antioxidant dietary fiber; the last-named being the one that presents the greatest bioactive properties. In recent years, the search for novel sources of dietary fiber with antioxidant properties focused widely on plant food by-products. Jiménez-Escrig[9] reported that the pulp and peel of guava fruit are good sources of natural antioxidants that could be used to obtain dietary fiber with antioxidant activity. In another study, Chantaro[12] reported the feasibility of using carrot peels, a byproduct from the food industry, to produce dietary fiber with antioxidants associated (phenolic compounds and carotenoids), which may be used as a food ingredient. Pineapple shells were reported as a promising source of dietary fiber (composed of 70.6% dietary fiber) containing a high concentration of associated phenolics (mainly

Table 1 Total dietary fiber (TDF) and extractable polyphenols (EP) in raw fruits, fruit byproducts and sources of antioxidant dietary fiber

	TDF (% dry matter)	EP (mg GA g^{-1} dry matter)	Reference
Raw fruit			
White guava	5.3	1.5	
Red guava	2.7	23	
Carambola	2.7	22	
Mango	1.8	0.5	36
Papaya (cv. Red Lady)	1.7	0.4	
Blueberries	2.4	5.3	37
Grape	1.5	1.4	
Pineapple	1.4	—	
Apple	3.2	2.1	
Orange	1.1	3.3	
Strawberry	2.3	3.6	38
Durian	1.2	3.0	
Snake fruit	1.1	2.1	
Mangosteen	0.9	1.9	
Byproduct			
Banana peel	7.6	9.2	39
Guava peel	—	58	9
Mango peel	28	70	10
Mango seed	—	117	40
Jack fruit seed	—	27	41
Carrot peel	45	13	42
Pomegranate peel	—	249	45
Grape stem	77	116	
Antioxidant dietary fiber			
Cocoa powder	60	1.3	44
Guava pulp	48	26	
Guava peel	49	77	9
Jamaica	33	61	45
Orange-lime	69	—	10
Pineapple shells	70	—	
Cauliflower	6.0	3.4	48
Mango peel	51	96	49
Cabbage leaf	51	3.4	50
Acaí	71	15	51

myricetin) that exhibits antioxidant activity. This property, together with the neutral color and flavor, makes it a suitable fiber for a wide range of applications as a food ingredient.[10] Vergara-Valencia *et al.*[43] obtained a mango dietary fiber concentrate with antioxidant capacity, which could be an alternative for the development of products with balanced dietary fiber components and low glycemic response. Lecumberri *et al.*[44] obtained a dietary fiber powder with intrinsic antioxidant capacity (derived from soluble polyphenols and condensed tannins) from cocoa. The by-products of the Prensal Blanc white grape (*Vitis vinifera*) are an excellent source of dietary fiber with antioxidant properties.[46] Nilnakara *et al.* obtained an antioxidant dietary fiber powder from cabbage outer leaves.[47] Rufino *et al.*[11] reported that BRS-Pará acaí fruits can be considered as an excellent source of associated dietary fiber/antioxidants.

In general, there is increasing interest to find new sources of dietary fibers with specific bioactive constituents that may add new healthy properties to the traditionally commercialized products. Fruits, cereals and grains are potential sources of this material. However, as mentioned, by-products, such as peels, seeds and unused flesh, can present similar or even higher contents of these bioactive compounds and have traditionally been undervalued. Nevertheless, it is widely known that plant foods are an excellent source for both isolated phenolic compounds and dietary fiber.

Dietary fiber and phenolic compounds as functional ingredients

In recent years, interest in nutrition and disease prevention has begun to drive consumer demand for value-added foods, or functional foods enriched with an ingredient able to provide or promote a beneficial action for human health.[51] These compounds are the so-called functional ingredients, which provide benefits additional to nutritional and energetic gains; and at the same time are able to improve the technological functionality of a food. The term "functional ingredient" is meant to convey the function of these new ingredients, which is to produce a positive health outcome *via* physiological activity in the body.[52] It has become recognized that these compounds markedly influence quality of life factors, such as modulation of performance or reducing risk of acquiring a variety of diseases, by modifying one or more physiologic processes.[53] There is a diverse group of compounds classified as functional ingredients, for example, carotenoids, flavonoids, dietary fiber, phenolic compounds, allyl compounds, glucosinolates, and peptides, among others.

Dietary fiber and phenolic compounds hold all the characteristics required to be considered as important functional ingredients, due to their physiological roles. Dietary fiber plays several important roles, including increasing the volume of fecal bulk, decreasing the time of intestinal transit, decreasing cholesterol and glycaemia levels, trapping substances that can be dangerous for the human organism (mutagenic and carcinogenic agents), and stimulating intestinal microflora proliferation.[4] Moreover, dietary fiber improves the technological properties of the food, such as water-holding capacity, swelling capacity, and increasing viscosity, texture or gel formation, which is essential in formulating certain food products[54] (Fig. 2). In the case of beverages and drinks, the addition of dietary fiber increases their viscosity and stability. Additionally, fiber-rich byproducts may be incorporated into food products as inexpensive, non-caloric bulking agents for partial replacement of flour, fat or sugar, as enhancers of water and oil retention and to improve emulsion or oxidative stabilities.[54] Also, phenolic compounds are involved in decreasing the risk of chronic diseases, such as cardiovascular disease and cancer, and are useful against lipid peroxidation in food processing.[19,55] There are many benefits that these compounds provide as functional ingredients; therefore, dietary fiber with associated phenolic compounds is a novel promising material for the food processing and nutrition industry, because it combines the properties of both components in a single material.

Various foods, such as bread, meat, fish and beverages,[13,56,57] have been enriched with different sources of dietary fiber and phenolic compounds with satisfactory results (Table 2). The literature contains many reports about the addition of dietary fiber to food products, such as baked goods, beverages, confections, dairy, frozen dairy, meat, pasta and soups. Among the most known and consumed dietary fiber-enriched foods are breakfast cereals and bakery products such as whole-grain breads and cookies,[61,62] as well as milk- and meat-derived products. Some types of soluble fibers, such as pectins, inulin, guar gum and carboxymethyl-cellulose, are utilized in milk products.[62] Guar gum and inulin are added during cheese processing to decrease its percentage fat without losing its organoleptic characteristics. Moreover, for the elaboration of jams and marmalades, the most common added fibers are those consisting of pectins with different degrees of esterification, obtained mainly from fruits and are a factor in keeping the stability of the final product.[64] On the other hand, phenolic compounds as functional ingredients act as antimicrobials, antioxidants, flavorings and thickeners.[2] In general, phenolic compounds are added mainly into meat and fresh-cut fruits and vegetables to avoid enzymatic browning, lipid oxidation, bacterial contamination and increase the antioxidant capacity and health benefits of products. Therefore, delaying lipid oxidation and preventing bacterial cross-contamination are highly relevant to food processors. However, phenolic compounds are also attracting more and more attention not only due to their antioxidant properties, but as anti-carcinogenic and anti-inflammatory agents. Among the most common materials used as sources of phenolic compounds are herb extracts and citrus fruits.[69]

Several patents have been published about the addition of dietary fiber with associated phenolic compounds to increase the health benefits status of the supplemented foods. For example, Myllymaki[73] claimed the formulation of a rye cereal product having higher dietary fiber and phenolic content. This cereal is a good source of dietary fiber (38%) and also contains a significant fructan concentration (7 g/100 g), which according to the suggested new dietary-fiber concept is also a component of dietary fiber.

Table 2 Effect of functional foods enriched with dietary fiber, phenolic compounds and dietary fiber with associated phenolic compounds

Functional food	Functional ingredient	Source	Results	Reference
Cookies and bread	Dietary fiber	Mango	Products with balanced components and low predicted glycemic index response	43
Bologna cooked sausages	Dietary fiber	Lemon albedo	Similar sensory properties to conventional sausages but improvement in the nutritional properties	58
Cookies	Dietary fiber	Extruded wheat bran	Dietary fiber content was increased and the glycemic index was low	59
Yogurt	Dietary fiber	Acacia	Greater therapeutic effects in patients with irritable bowel syndrome	60
Cupcakes	Dietary fiber	Oat and wheat	Addition of 30% dietary fiber improved quality characteristics of cupcakes. Also prolonged the shelf-life of the cakes by delaying the moisture loss and the increase in crumb firmness	63
Fresh potatoes	Phenolic compounds	Oregano	Increase in antioxidant activity and reduction of acrylamide content	65
Bread	Phenolic compounds (proanthocyanidins)	Grape seed	High antioxidant activity and reduce the Nε(carboxymethyl) lysine formation, related to health risks	66
Cooked pork meat patties	Phenolic compounds	Rapeseed and pine bark	Inhibition of protein oxidation between 42 and 64%	67
Cheese product	Phenolic compounds	Herb extracts (cinnamon stick, oregano, clove, pomegranate peel, and grape seed)	Plant extracts were effective against *Listeria monocytogenes*, *Staphylococcus aureus*, and *Salmonella enterica*. Also, extracts increased the stability of cheese against lipid oxidation	68
Dough biscuits	Dietary fiber with associated phenolic compounds	Mango peel	Dietary fiber and polyphenols content increase 14% and 90%, respectively	70
Cake	Dietary fiber with associated phenolic compounds	By-product of apple juice	Increase the dietary fiber and polyphenols content, to 14% and 7.16 mg g^{-1}, respectively	71
Yogurt and salad dressing	Dietary fiber with associated antioxidants	Wine grape pomace	Increase dietary fiber and total phenolic content, also delay lipid oxidation of samples during refrigeration storage	72
Fish mince horse mackerel	Dietary fiber with associated phenolic compounds	*Fucus vesiculosus* spp.	Prevented lipid oxidation during 5 months of frozen storage at −20 °C. Also, reduced total yield after thawing and cooking after up to 3 months of frozen storage	14
Macaroni products	Dietary fiber with associated phenolic compounds	Mango peel	Enhance nutritional and technological quality. The dietary fiber content increased 9% and exhibited improved antioxidant properties	49

Another patent reports the preparation process and health benefits of a grape antioxidant dietetic fiber concentrate.[74] The powder obtained from black or white grape skins had the following characteristics expressed in dry weight: total dietary fiber content of 65–80%, 15–25% bioactive compounds content (soluble and insoluble condensed tannins, flavonoids, proanthocyanidins and other polyphenols), 11 to 15% protein, and 5 to 8% crude fat.[74] According to these authors, the incorporation of dietary fiber and phenolic compounds can be utilized for the preparation of functional foods presumably with improved health benefits and technological properties. However, these studies need to be accompanied by quality and sensory evaluations.

Dietary fiber with associated phenolic compounds obtained from wine grape pomace was added to yogurt and salad dressings.[75] The addition resulted in a 35–65% reduction of peroxide values in all samples. Total phenolic content and DPPH radical scavenging activity were 958–1340 mg GAE kg^{-1} product and 710–936 mg AAE kg^{-1} product, respectively. The addition was mostly liked by consumers, based on the sensory study. Fiber extract from *Lentinus edodes* mushrooms containing 514 g kg^{-1} of (1–3)-beta-glucans was added to wheat flour.[76] Replacement of a portion of wheat flour with the extract resulted in lower values of pasting parameters and also caused significant changes in starch gelatinization. When the same extract was incorporated into cake formulations, batter viscosity increased with more shear-thinning behavior and elastic properties improved. However further studies are needed to find the health benefits of this addition and particularly the presence of associated phenolic compounds in edible mushrooms.

The use of dietary fiber with associated phenolic compounds from grapes has been reported to inhibit food lipid oxidation. Sanchez-Alonso *et al.*[13] observed a 57% lipid inhibition measured by TBARS in frozen minced mackerel patties treated with 2% grape antioxidant dietary fiber. The authors reported that this protective effect could be either by the chelation action of fiber over prooxidant metals or the antioxidant capacity of the polyphenols present in the material. Similar results were observed for raw and cooked chicken hamburgers stored 14 days at 4 °C, in which not only the lipid oxidation was inhibited, but also an increase of radical scavenging capacity in the fortified hamburgers was observed.[15] Even though there are no studies of the effect of these protected food products over total plasma oxidative status of consumers, it may be hypothesized that the consumption of these products may exert a beneficial effect over the consumer as a result of less free radical intake.

Although great achievements have been made by using dietary fiber and phenolic compounds as functional ingredients, as well as the material that combines both substances, further investigations about structure and functionality within the food matrices (proteins, lipids and water activity) and the bioavailability effects after intake are needed.

Dietary fiber effect over phenolic compounds in the human digestive tract

As stated above, in recent years, there has been a growing interest among researchers in the formulation of food products with dietary fiber and phenolic compounds due to their linkage to human health. However, consumption of food rich in some nutrients or bioactive compounds does not guarantee their bioavailability in the digestive tract, therefore, the biological effect of the nutrients/bioactive compounds is not insured.[77] The bioavailability or absorption in the gut is in many cases quite uncertain or varies for the same food depending on processing conditions, presence of other compounds, and so on. Furthermore, there are some specific factors that could affect the absorption of the molecules in the gut, such as food microstructure, structure and molecular weight of the compound, and chemical interactions between food constituents.[29] This last factor is very relevant because recent scientific data appear to demonstrate that, in the case of certain nutrients and bioactive compounds, the state of the matrix of natural foods or the microstructure of processed foods may improve or hinder their nutritional response *in vivo*. In fact, it has recently been stated that the generation of functional foods fortified with fiber rich and phenolic compounds could result in a loss of absorption of the antioxidants, because fiber may trap the antioxidant molecules, decreasing the proposed food functionality.[18] However, some evidence suggests that phenolic compounds entrapped into dietary fiber can reach the colon and exert a biological effect, playing an important role in intestinal health.[24]

The next sections describe the possible interactions that may arise between phenolic compounds and dietary fiber and how these interactions can affect the bioavailability of these compounds.

Dietary fiber and phenolic compounds chemical interactions

As previously described, some plant foods are rich sources of dietary fiber that carry putatively bioactive compounds, phenolic compounds in particular, embedded in them; these previous studies indicate that both components are able to interact chemically in the food matrix.[7] Phenolic compounds have both hydrophobic aromatic rings and hydrophilic hydroxyl groups with the ability to bind to polysaccharides and proteins at several sites on the cell wall surface.[7] They are linked by hydrogen bonding (between the hydroxyl group of phenolic compounds and oxygen atoms of the glycosidic linkages of polysaccharides), hydrophobic interactions, and covalent bonds such as ester bonds between phenolic acids and polysaccharides (Fig. 3). Interactions can be dependent on particle size, specific porosity and surface properties, which can restrict the size of the molecules that penetrate. Pore size in the cell wall can range from 4 to 10 nm in diameter, which may restrict penetration of phenolic compounds with molecular masses larger than 10 kDa (equivalent to 34 units to catechin).[78]

Dietary fiber can interact and bind during gastrointestinal digestion with antioxidants present in the food matrix. These interactions can be either hydrogen bonds, strong (covalent) interactions or physicochemical entrapment exerted by dietary fiber.[18] Considering that these bonds are weak, they are stable only above a minimum critical length, and their formation and disruption often occur as sharp, cooperative processes in response to comparatively small changes in, for example, pH or solvent quality in the gastrointestinal tract (that is the nature and concentration of dissolved solids in the chyme). In this context, the possible interactions that may arise between dietary fiber and phenolic compounds can decrease or delay their absorption in the gut, as mentioned in early sections.

Effect on bioaccessibility and bioavailability

Bioavailability is defined as the proportion of a nutrient that is digested, absorbed, and utilized in normal metabolism; bioaccessibility is a commonly used term to describe the amount of an ingested nutrient that is available for absorption in the gut after digestion.[18,77] In this sense, bioavailability strictly depends on bioaccessibility, and it is well known that the biological properties of nutrients and bioactive compounds, such as phenolic compounds, depend on this release–absorption process. It has been reported that phenolic compounds are released from the food matrix in the upper area of the gastrointestinal tract by direct solubilization in the intestinal fluids at physiological conditions (37 °C, pH 1–7.5) and/or by the action of digestive enzymes (enzymatic hydrolysis of protein, carbohydrates, and lipids favors the release of phenolics from the food matrix).[24] These accessible compounds (low molecular weight phenolics) are at least partially absorbed through the small intestine mucosa. However, another group of phenolics are not bioaccessible; these compounds pass undissolved and unaltered through the upper intestine in association with the food matrix, including dietary fiber, which alters the efficiency of the physical, enzymatic, and chemical digestion processes.[79] Moreover, this bioavailability can be even lower for large molecular weight food polyphenols, as is the case of hydrolyzable and condensed tannins and complex flavonoid conjugates with several sugars and acylated with hydroxycinnamic acids. Therefore, it is generally accepted that the bioavailability of phenolics is rather low, even though high variability in the bioavailability of the different polyphenols may be observed, and can be expressed as the relative urinary excretion of the intake range, from 0.3% for anthocyanins to 43% for isoflavones such as daidzin.[80]

Several factors can explain this variability, among them the food matrix, particularly dietary fiber components, plays an important role. There is ample evidence that the physical state of the food polysaccharides plays a key role in the bioaccessibility of many bioactive food components, such as antioxidants.[77,81,82] It is known that dietary fiber can reduce the bioavailability of macronutrients and biomolecules, especially fat, and some minerals and trace elements in human digestion.[83] In general, the two main effects of dietary fiber in the foregut are to prolong gastric emptying time and to retard absorption of nutrients.[84] Both are dependent on the physicochemical characteristics of the fiber, and in particular, its influence on the viscosity of the bolus. Dietary fiber can act in the small intestine in three main physical forms: as soluble polymer chains in solution, as insoluble macromolecular assemblies, and as swollen, hydrated, sponge-like networks.[85] Therefore, the dominant factors involved in the influence of dietary fiber on antioxidant digestion are: (1) physical trapping of antioxidants within structured assemblies, such as fruit tissue, and (2) enhanced viscosity of gastric fluids restricting the peristaltic mixing process that promotes transport of enzymes to their substrates, bile salts to unmicellized fat, and soluble antioxidants to the gut wall.[86] For these reasons, interactions of phenolic compounds with dietary fiber are expected and may affect their releasing during digestion and interfere with absorption in the gut.[18]

In this context, the limited bioavailability of antioxidants associated with dietary fiber is determined by their low bioaccessibility in the small intestine, due to the physical and chemical interactions between antioxidants and the indigestible polysaccharides of the cell wall. However, all non-absorbable antioxidants reach the large intestine and remain in the colonic lumen where they may contribute to a healthy antioxidant environment.[78]

Functional and biological properties in the gut

Dietary fiber associated with phenolic compounds possesses some functional and biological properties, such as antioxidant capacity and colonic fermentation.[87] The appreciable amount of phenolic compounds linked to or entrapped by dietary fiber provides a significant antioxidant capacity that may have pronounced effects on biological systems, such as the gastrointestinal tract. Phenolic compounds associated with dietary fiber may have significant effects in intestinal health. The antioxidant dietary fiber is transported largely unaltered along the small intestine all the way to the colon. The intestinal microbiota ferments the antioxidant dietary fiber matrices, and phenolic compounds are gradually released in the intestinal lumen and partially absorbed by gut epithelial cells. Therefore, non-absorbable phenols and non-fermented phenolic compounds remain in the colonic tissue, scavenging free radicals and counteracting the effects of dietary fiber pro-oxidants[7] (Fig. 4). At the same time, the partial or total fermentation of dietary fiber constituents (*e.g.* cellulose, hemicelluloses, pectins, resistant starch, fructans, arabinoxylans) releases several beneficial short-chain fatty acids (SCFA), such as phenylacetic, phenylpropionic and phenylbutyric acids.[78] These compounds may exert systemic effects in conjunction with

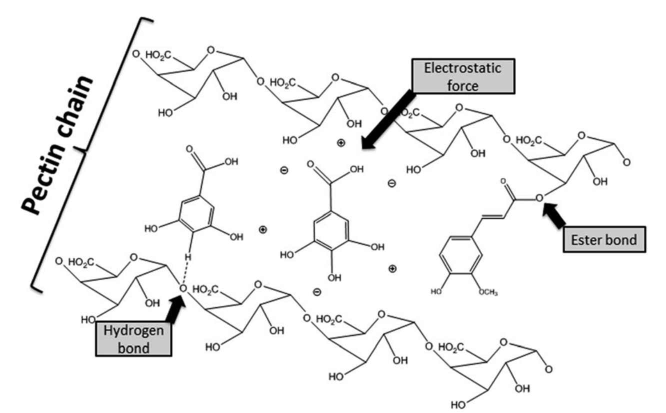

Fig. 3 Types of interactions between phenolic compounds and dietary fiber.

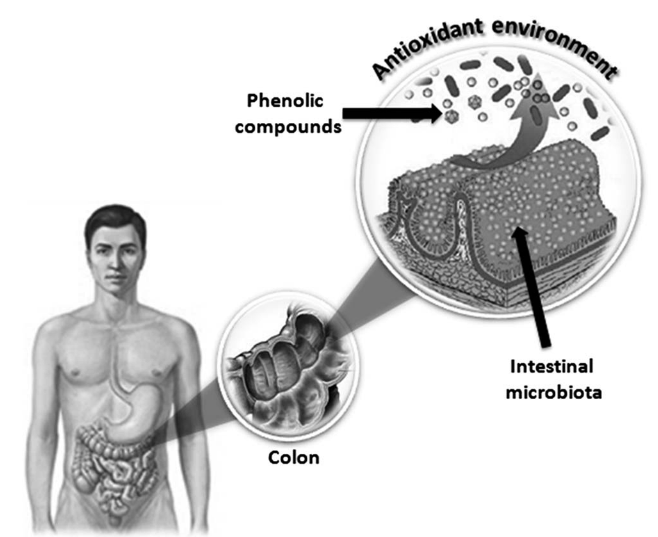

Fig. 4 Colon antioxidant environment formed by the action of intestinal microbiota that ferments the dietary fiber matrices, and phenolic compounds are gradually released at the intestinal lumen and partially absorbed into gut epithelial cells.

phenolic compounds, for example the induction of cellular differentiation and apoptosis.[88,89] Moreover, epidemiological studies have shown an inverse association between dietary fiber with associated antioxidants consumption and colon cancer, mainly due to the effect of SCFA (butyrate hypothesis) on the modulation of genes associated with this disease.[90] Recently, Lizarraga *et al.*[91] analyzed the effect of consumption of grape antioxidant fiber over 26 393 mice genes, observing that 363 genes were upregulated and 641 downregulated. From the analysis of these results, the authors suggested that the beneficial health effect was because the grape antioxidant fiber consumption downregulated nuclear receptor signaling, lipid biosynthesis (TNF and PPARα) and energy metabolism, pathways associated with obesity and cancer. At the same time, antioxidant and detoxification enzymes (Fase I and II) and apoptotic (BFAR and CARD14), immune system and tumor suppression genes (NBL1) were upregulated. These results clearly show the beneficial effect of dietary fiber with associated phenolic compounds. In particular, phenolic compounds, dietary fiber components and their metabolites come into contact with the gut wall for up to several hours (more than 24). For this reason, the antioxidant environment formed in the colon could modulate the incidence of certain kinds of degenerative diseases, such as colon cancer.

Furthermore, the beneficial effect of consumption of dietary fiber with phenolics has been associated with the proliferation of lactobacilli, and to a lesser degree Bifidobacteria, both *in vitro* and *in vivo*, and an inhibition of pathogenic bacteria (*Escherichia coli*, *Clostridium*) that improves the overall gastrointestinal health. This beneficial effect may be explained in terms of the presence of phenolic compounds such as (+)-catechins, (−)-epicatechin and (−)-epicatechin-3-*O*-gallate, and tannins in the material, which exert antimicrobial activity against pathogenic bacteria in the gut. The same authors suggested that dietary fiber with phenolic compounds embedded modifies the gut morphology improving gastrointestinal absorption.

Conclusion and future research

The use of phenolic compounds and dietary fiber as food ingredients is of great interest not only as a means of improving the functionality of food products, but also to formulate functional foods with health benefits, such as reducing cholesterolaemia, modifying the glucaemic response, and preventing the development of cancer and some cardiovascular diseases. Furthermore, the physicochemical association between these two bioactive substances (fiber and phenolic compounds) that has created a new material that combines the functional properties of both fiber and antioxidants (mainly antioxidant capacity) is well known, and in the last few years it has been used as a functional ingredient. However, there is evidence that this association may not only exert beneficial effects, but also some unwanted effects, because dietary fiber may affect the bioaccessibility and bioavailability of phenolic compounds and consequently reduce fiber's healthy and biological effects. Nevertheless, it has been stated that due to these fiber–phenolic compounds interactions, an appreciable amount of phenolic compounds are carried out by dietary fiber through the gastrointestinal tract, producing antioxidant metabolites in the colon and creating an antioxidant environment for the prevention of diseases such as colon cancer. However, future research is needed to verify this hypothesis.

In this context, research on the dietary fiber–phenolic compounds association offers to be a very promising area. Future work is needed to elucidate the real contribution of functional foods enriched with dietary fiber to the well-being of consumers. For this reason, more studies on bioaccessibility and bioavailability, both *in vitro* and *in vivo*, from different formulations in new products and sources of dietary fiber–phenolic compounds are needed. In addition, the role of fiber as a controlled release system of bioactive compounds in the colon must be studied in more detail.

Acknowledgements

We thank CIAD and CONACYT-México for financial support. This work is part of the project "Nutrigenómica e interacciones moleculares de fenoles y fibra dietaria del mango "Ataulfo" (Mangifera indica, L.) en un sistema Murino" Project 179574CB-2012-01.

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