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Function of Dietary Fibers as Food Ingredients

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ABSTRACT—Dietary fiber imparts both nutritional and functional properties to foods. This review deals with (1) the classification of dietary fiber, (2) the plant cell wall models, (3) the relations between structure and physicochemical and functional properties of dietary fiber and (4) the applications of dietary fiber in foods. Dietary fiber can be classified in terms of source, plant function, solubility, charge and topology. Plant cell wall models are presented to provide information on the interconnections of dietary fiber components which determines the content of soluble and insoluble dietary fiber content. In reality, physicochemical and functional properties of dietary fiber originate from their structural features. Thus, of primary importance is to clearly characterize the structural factors such as chemical constituents, charge, branching degree, conformation and etc. Dietary fibers possess a variety of functional properties in food systems, which thus make them useful in food application. In particular, rheology and gelation of water-soluble gums or hydrocolloids are discussed for their effects on food quality. A guideline is also listed for the gum selection to meet the best product requirements.

Keywords□Dietary fiber, Nutritional properties, Functional properties

Introduction

Dietary fiber is a valuable nutritional concept embodying the resistance to digestion in the small intestine, which decreases the rate of carbohydrate and lipid absorption, and exerts a beneficial effect on large intestinal function by acting as a substance for fermentation (Cummings and Englyst, 1991). In recent years, there has been increasing consumer awareness for health foods (Caragay, 1991; Harris, 1992; Raj an Clancy, 1992; Schmidl and Labuza, 1992). Since dietary fiber possess a variety of positive physiological functions, high-fiber foods can be a good response for consumer demand. In reality, increased dietary fiber content has become a dominant marketing claim for new food product introduction (McCormick, 1988).

This article reviews (1) the diverse classification of dietary fibers, (2) the plant cell walls as dietary fiber sources, (3) the relations between structure and properties of dietary fibers and (4) the applications of dietary fibers in foods. This attempt will contribute to clarifying the functional role of dietary fibers on the basis of structural information, and eventually to extending the applicability to food product development.

Classification of Dietary Fibers

Dietary fibers are composed of complex chemical consitutents each with the unique chemical and structural arrangment, which in turn impart specific physicochemical, functional and nutritional properties (Dreher, 1987). These components undergo numerous changes during the growth and maturation of plant tissue and also during the processing, storage and cooking of foodstuffs (Dreher, 1987). Thus, a universal organization of dietary fibers is difficult because of the wide variation from source to source. In this review, dietary fibers are classified in terms of source, plant function, solubility, charge and topology. This diverse classification will lead to understanding more clearly the relations between structure and function of dietary fibers.

Source

Table 1. Dietary fiber sources (Selvendran *et al.*, 1987)

Main components of a mixed diet	Tissue types	Main constituent groups of DF polymers[a]
Fruits and vegetables	Mainly parenchymatous	Pectic substances (e.g., arabinans and methyl esterified rhamnogalacturonans), cellulose, hemicellulosic polymers (e.g., xyloglucans), and some proteins[b] and phenolies
	Partially lignified vascular tissues	Cellulose, hemicelluloses (e.g., glucuronoxylans), lignin, and some pectic substances and proteins[b]
	Cutinized epidermal tissues	Cutin and waxes
Cereals and products	Parenchymatous (endosperm and aleuronelayer)	Hemicelluloses (e.g., arabinoxylans and/or β-D-glucans) and some cellulose, proteins,[b] and phenolics
	Partially lignified seed coats	Hemicelluloses (e.g., glucuronoarabinoxylans), cellulose, lignin, and phenolics and some proteins[b]
Seeds other than cereals (e.g., legume seeds)	Parenchymatous (e.g., pea cotyledons)	Cellulose, pectic substances, hemicelluloses (e.g., xyloglucans) and some proteins[b]
	Cells with thickened endosperm walls (e.g., guar seed splits)	Galactomannans and some cellulose, pectic substances, and proteins[b]
Seed husk of *Plantago ovata* (ispaghula husk)	Mucilage of epidermal cells	Mainly highly branched acidic arabinoxylans
Polysaccharide food additives	–	Food gums-gum arabic, alginates, carrageenan, guar gum, carboxymethylcellulose, modified starches, etc.

[a]The polymers are listed in approximately decreasing order of amounts

[b]Most of the proteins are present as components of glycoproteins or proteoglycans

Classification of dietary fibers based on sources is shown in Table 1. It can be seen that dietary fibers can be obtained from a wide range of sources. Here it is noteworthy that gums or hydrocolloids are also good sources of dietary fibers.

Plant function

The conventional components of dietary fibers can be also divided according to plant function as follows (Schneeman, 1986):

(a) Structural polysaccharides: cellulose, pectin and hemicelluloses

(b) Structural nonpolysaccharides: lignin

(c) Nonstructural polysaccharides: gums and mucilages

Solubility

Depending on the solubility, dietary fibers can be categorized into either soluble or insoluble. Water solubility is a simple measure that gives information about the physiological effects of dietary fibers (Stephen and Cummings, 1979). Water-soluble dietary fibers such as pectins, gums and mucilages function to lower the plasma cholesterol level, whereas water-insoluble dietary fibers such as cellulose and some hemicelluloses impart laxative properties (Schneeman, 1987; Schneeman, 1989, Cummings and Englyst, 1991).

Charge

Dietary fibers can be classified by either neutral or ionic (sulfated, carboxylated, phosphorylated, etc). It is generally recognized that the ionic polymers are greatly affected by environmental pH or ionic strength.

Topology

Dietary fibers can be also classfied on the basis

Table 2. Comparison of functional properties of linear and branched carbohydrate polymers (Hwang and Kokini, 1991)

Functions	Linear Branched
Solubility	<
Gelatinization	<
Gelling	>
Retrogradation	>
Film Formation	>
Freeze-Thaw Stability	<
Interaction Properties	>

Table 3. Comparison of rheological properties of linear and branched polymers (Hwang and Kokini, 1991)

Properties	Linear Branched
Radius of Gyration	>
Intrinsic Viscosity	>
Zero-Shear Viscosity	<
Zero-Sear Recoverable Compliance	<
Shear rate Dependence of Viscosity	<
Extensional Viscosity	<
Thermal Sensitivity of Viscosity	<

Table 4. Plant cell wall components (Brett and Waldron, 1990)

Components	Polymers
Cellulose	β-1,4 glucan
Pectin	homogalacturonan
	rhamnogalacturonan
	arabinan
	galactan
	arabinogalactan
Hemicelluloses	xyloglucan
	arabinogalactan
	xylan
	glucomannan
	mannan
	glucuronomannan
	callose (β-1,3 glucan)
Proteins	extensin
	arabinogalactan-protein
	others, including enzymes
Phenolics	lignin
	ferulic acid
	coumaric acid
	truxillic acid

of their topology, i.e., either linear or branched. The functional and rheological properties influenced by the presence of sidechains are presented in Table 2 and 3, respectively. It can be seen that branching can alter variety of functional and rheological properties of polymers. The branching factors affecting the functional properties of carbohydrates are chemical constituents, size, charge and distribution. The interested reader is referred to the report of Hwang and Kokini (1991) in details.

Plant Cell Wall Models

The most common source of dietary fibers are associated with the plant cell walls, consisting of a heterogeneous mixture of macromolecules with varying degree of crosslinking to form a complex matrix (Schneeman, 1989; Dintzis, 1982). The major cell wall components are given in Table 4. Northcote (1972) stated that the constituents of cell walls fall into three groups: fibrillar polysaccharides (cellulose), matrix polysaccharides (pectin and hemicelluloses) and encrusting substance (lignin). The structural features of plant cell wall constituents were described in detail elsewhere (Aspinall, 1980; Dey and Brinson, 1984; Bacic *et al.*, 1988).

Fig. 1 shows a simplified primary cell wall model of dicotyledonous plants, which is based on the models of Keegstra *et al.*, (1973) and Albersheim (1975). This model depicts that hemicellulosic xyloglucans are held to the cellulose fibrils by hydrogen bonds, where some reducing ends of some xyloglucan molecules may be convalently bound to arabinogalactans which are the major sidechains of pectin molecules. A pectic rhamnogalacturonan molecule is covalently connected to several arabinogalactan chains, each radiating from a different cellulose microfibril. Thus, the cellulose-xyloglucan framework is embedded in a gel matrix of pectic polysaccharides crosslinked in part by Ca^{+2}. Following the cell wall model of Albersheim (1975), many new models have been

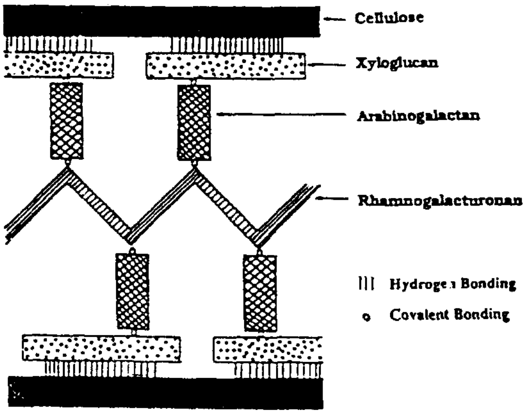

Fig. 1. Interconnections between polysaccharides in the primary cell wall (John and Dey, 1986).

proposed depending on the plant sources and the developmental stages. Despite some changes, however, they are in essense embodied in the Albersheim's model (John and Dey, 1986). The interested reader is referred to other detailed reviews for the plant cell wall models (Aspinall, 1980; Selvendran, 1983; Dey and Brinson, 1984; John and Dey, 1986; Bacic *et al.*, 1988; Brett and Waldron, 1990).

As stated earlier, dietary fibers can be distinguished with respect to their solbility for the isolated dietary fiber components. In reality, however, various dietary fibers exist as the complex matrix in the plant cell walls. Therefore, each plant source possesses its soluble and insoluble dietary fiber fractions depending on the degree of interconnections in the cell walls. Table 5 demonstrates the dietary fiber content for some plant sourcs. The comprehensive data on the dietary fiber content for other plant sources can be found in the references (Anderson, 1986; Dreher, 1987; Anderson and Bridges, 1988; Englyst, 1989). Here it should be pointed out that these ratios can be altered, if the structural interconnections are successuflly modified by either chemical or enzymatic means.

Structure and Properties of Dietary Fibers

Of signficant importance is to understand the

Table 5. Dietary fiber content of some selected foods[a] (McCormick, 1988)

Fiber source	Total dietary fiber	Soluble fiber	Insoluble fiber
Cereals, Legumes			
Soybean bran	45~55	17.5	37.5
Barley bran	65.0	3.0	62.0
Corn bran	92.0	0.7~0.8	91.0
Oat bran	22.2	10.5	11.7
Rice bran	29~34	9.0	6~20
Rye bran	30~35	3.0~5.0	30.0
Wheat bran	42.0	3.0	39.0
Gums			
Acacia	–	84~90	–
Arabic	–	94.2	–
Cellulose	–	–	99.0
Carrageenan	–	78.0	–
Xanthan	–	85.0	–
Fruits, Vegetables			
Apple	57.7	1.7	56.0
Citrus	72.0	29.0	43.0
Pear	56.0	1.5	54.5
Tofu Fiber	55~60	2.0~3.0	52~57

[a](% Dry weight basis)

Table 6. Chemical composition of dietary fiber (Schneeman, 1989)

Fiber component	Chemical components	
	Main Chain	Side Chain
Polysaccharides		
Cellulose (1,4 β-linked)	Glucose	—[a)]
Noncellulose		
Hemicellulose		
Arabinoxylan	Xylose	Arabinose
Galactomannan	Mannose	Galactose
Glucomannon	Galactose	Glucuronic acid
Pectic substances	Galacturonic acid	Galactose, glucose
		Rhamnose
		Arabinose
		Xylose
		Fucose
Beta-glucans(1,3 β-and	Glucose	—
1,4 β-linked)	Galactose, mannose	Galactose
	Glucose, mannose	
	Arabinose, xylose	
	Galacturonic acid, rhamnose	
Gums	Galactose	Xylose
	Glucuronic acid, mannose	Fucose
	Galacturonic acid, rhamnose	Galactose
Algal polysaccharides	Mannose	Galactose
	Xylose	
	Guluronic acid, mannuronic acid	
	Glucose	
Nonpolysaccharides		
Lignin	Sinapyl alcohol	
	Coniferyl alcohol	
	p-Coumaryl alcohol	

[a)]No side chain

relations between structure and properties of dietary fibers for their applications in food systems. The impact the dietary fiber has on human physiological activities and food properties has attracted much attention from health professionals and food scientists (Dreher, 1987). From the physiological point of view, dietary fibers act like sponge, which results in binding water, nutrients, bile acids and carcinogens as it passes along the gastrointestinal tract. From the viewpoint of food applications, soluble dietary fibers such as gums are of special interest due to their functional properties such as viscosity, thickening and gelation. These functional chracteristics determine the selection of dietary fibers for specific food use. To date many attempts have been made to predict the physiological characteristics and food uses of dietary fibers on the basis of physicochemical and functional properties.

Structure

Table 6 shows the chemical constituents consisting of dietary fibers. It is noted that a majority of dietary fibers are composed of heterogeneous

Table 7. Physicochemical properties of dietary fibers and their physiological significance (Cummings and Englyst, 1991)

Properties	Physiological Effects
Water-holding capacity	Rate of fermentation, gastrointestinal transit time, stool weight
Solubility/Viscosity	Carbohydrate and sterol absorption in small intestine
Surface charge	Cation binding, mineral absorption, bile acid metabolism
Particle size	Rate of fermentation, gastrointestinal transit time, stool weight
Effect of food structure	Chewing, gastric empting, satiety, rate of nutrient release

sugar constituents. Zimmermann (1979) listed the factors affecting physicochemical and functional properties of polysaccharides as follows:

(a) Molecular components: hexoses, pentoses, uronic acids, ring configuration

(b) Functional groups: carboxyl, hydroxyl, sulfate ester, phosphate ester, methyl ester, localization in the molecule, and degree of substitution

(c) Structure: glycosidic linkage, type of structure, degree of branching, degree of polymerization, distribution of basic units

(d) Conformation: helical, band, net, association, micelle

Physicochemical properties

Knowledge of the physicochemical properties of dietary fibers can act as an important guideline for predicting their physiological effects (Kay, 1982; Ink and David Hurt, 1987; Gordon, 1989; Ebihara, and kiriyama, 1990; Schweizer, T.F. and Würsch, 1991). The typical physicochemical properties of dietary fibers are summarized in conjunction with their physiological effects in Table 7. The details about these properties were also reported previously (Selvendran *et al.*, 1987). Water soluble dietary fibers can form viscous solutions due to their high hydration capability. Cummings and Englyst (1991) stated that viscosity of polysaccharide solutions is determined by chemical structure, molecular weight, concentration, temperature, pH and the presence of other substances such as proteins and divalent cations. The viscosity slows gastric emptying and the diffusion and absorption of nutrients such as glucose and sterol (John, 1990). Thus, solubility and viscosity are key factors affecting the physicochemical and correspondingly physiological properties of dietary fibers (Schneeman, 1986).

Table 8. Functional properties of hydrocolloids (Glicksman, 1982)

Function	Example
Adhesive	Glaze, icings, frostings
Binding agent	Pet foods
Bodying agent	Dielectric beverages
Crystallization inhibitor	Ice cream, sugar syrup, frozen foods
Clarifying agent	Beer, wine
Cloud agent	Fruit drinks, beverages
Coating agent	Confectionary, fabricated onion rings
Dietary fiber	Cereals, breads
Emulsifier	Salad dressings
Encapsulating agent	Powdered flavor
Film former	Sausange casings, protective coatings
Flocculating agent	Wine
Foam stabilizer	Whipped toppings, beer
Gelling agent	Puddings, desserts, confectionery
Molding	Gum drops, jelly candies
Protective colloid	Flavor emulsions
Stabilizer	Salad dressings, ice cream
Suspending agent	Chocolate milk
Swelling agent	Processed meat products
Syneresis inhibitor	Cheese, frozen foods
Thickening agent	Jams, pie filling, sauces
Whipping agent	Toppings, marshmallows

Functional properties

Gums or hydrocolloids impart various functional

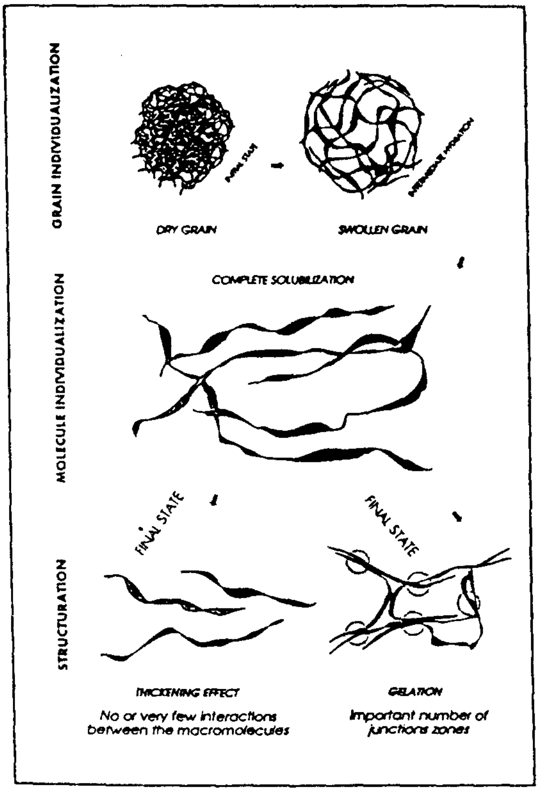

Fig. 2. Dispersion, solubilization and structuration of hydrocolloids.

properties, which makes them useful in a wide variety of food applications (Glicksman, 1982). Table 8 related functional properties of hydrocolloids for food uses. Among these properties, key properties are rheology and gelation, which in turn affect food systems in numerous ways such as in thickening, emulsification, texture and stabilization of taste and flavor (Pomeranz, 1985). Fig. 2 depicts solubilization of food gums and subsequent gelation. In this section, functional properties of dietary fibers are discussed with particular emphasis on rheology and gelation.

Rheology: Rheology is defined as a science of flow and deformation (Bingham, 1922). Thus, rheology is concerned with the relationships between forces, deformations and time and may also include temperature and other related parameters (Glicksman, 1982). Matter starts to flow when it is acted upon by force. Viscosity, defined as the resistance against flow, is the basic rheological property which characterizes the flow behavior of food systems.

Gum solution can be classified as Newtonian or non-Newtonian. In the Newtonian system, the shear stress is directly proportional and dependent on the shear rate, and viscosity is independent of the shear rate. This is true only for extremely dilute gum solutions. Most gum systems, however, are of a non-Newtonian nature (Sharma, 1981). The viscosity of gums relies on many factors including viscosity type, concentration, temperature, molecular size and conformation, shear conditions, pH, water holding capacity and electrolystes (Zimmermann, 1979). Polysaccharide, rheology was discussed in more detail elsewhere (Morris and Ross-Murphy, 1981; Launay *et al.*, 1986, Morris, 1989).

Gelation: Only a few gums have true gelling properties (Glicksman, 1982). Gums have varying modes of gelation, which also leads to the distinct quality, stability and texture of gels formed. Gelling requires the intermolecular association for junction zones or crosslinking of polymer chains to form a three dimensional network (Morries, 1986). This gel matrix retains the liquid phase within it to form a firm and rigid structure having the ability to resist the flow. These associated regions for gelation can be also formed from the mixed gum systems. For example, both xanthan and locust bean galactomannan alone are non-gelling polysaccharides in water (Szczesniak, 1986). However, their mixture interacts strongly, leading to the formation of a three-dimensional elastic gel (Dea *et al.*, 1977; Shatwell *et al.*, 1991). Typical gel characteristics of gums are summarized in Table 9.

Application: Practical Uses

Information on the physicochemical and functional properties of dietary fibers may be useful in formulating dietary fiber-enriched foods with optimal nutritional and new food product development impact (Dreher, 1987). Solubility is a key factor to determine the type of fibers are employed for

Table 9. Hydrocolloid gelling system (Glicksman, 1982)

Hydrocolloid	Solubility		Affected by electrolytes	Effect of heat	Gelling mechanism		Special conditions	Type of texture	Appearance	Applications
	Hot	Cold			Thermal	Chemical				
Gelatin	×		No	Melts at room temperature	×			Tender elastic	Clear	Desserts, confections, canned meat
Agar	×		No	Can withstand autoclaving	×			Firm, brittle	Clear	Canned meat, confections, bakery icings
x-Carrageenan	×		No	Does not melt at ambient temperature	×		Requires potassium cation for gelling	Brittle	Clear	Desserts, canned meets and pet food flan puddings
x-Carrageenan locust bean gum	×		No		×		Requires pottassium for gelation	Elastic	Cloudy	Desserts
x-Carrageenan	×		No		×		Requires calcium for gelation	Tender, elastic	Clear	Aseptic canned desserts
Furcellaran	×		No		×		Requires potassium for gelation	Brittle water gel, tender milk gel	Clear	Flan, puddings
Sodium alginate		×	Yes	Nonmelting and irreversible		×	Reacts with calcium to gel	Brittle	Clear	Dessert jels, milk puddings
Pectin	×		No		×		Requires sugar and acid to gel	Spreadable	Clear	Jams and jellies
Low methoxyl pectin		×	Yes			×	Reacts with calcium to gel	Brittle	Clear	Canned fruit/ milk dessert
Gum arabic		×	No		×			Soft, chewy	Clear	Confections
Starches	×		Yes	Retrograde on storage	×			Spreadable to soft rigid texture	Cloudy, opaque	Puddings desserts
Xanthan gum and locust bean gum	×		No		×		Both components required for gelation	Elastic, rubbery	Cloudy	

Table 10. Factors for gum selection (Blenford, 1986)

(a)	Solubility or dispersion of the gum and the effect of temperature, pH and shear
(b)	Rheological characteristics of the gel formed and the effect of temperature, concentration, pH and time on the viscosity- and gel-forming properties of the gum
(c)	Electrochemical behavior as it affects emulsification and product stability
(d)	Compatibility with other ingredients in the food product
(e)	Stability to pH, temperature and mechanical stress
(f)	Synergism with other gums
(g)	Effect on the color, odor and taste of the product
(h)	Microbial stabiltiy
(i)	Regulatory status for the intented application
(j)	Cost effectiveness

foods such as drinks and soups which demands solubilization as a prerequisite step for the developement of functional properties. In contrast, insoluble dietary fibers are added to foods such cereals and breads which do not require solubility.

The functional properties of gums also play an important role in the eating quality and final sensory acceptance of foods, especially of liquid food prodcts (Frost *et al.*, 1984). In particular, the flow behavior or rheology of a food system is closely relevant to its sensory and textural propterties such as body, consistency, sliminess, stickiness, creaminess and oiliness. Szczesniak and Farkas (1962) demonstrated that objective rheological measurements of gum solutions can be directly related to mouthfeel and other subjective measurements of sensory attributes. Glicksman (1982) and Kokini (1985) also stated that understanding the relationship between functional properties and sensory attributes can aid in the development of food products having high consumer acceptance. If textural attributes can be related to physical parameters, then they can be used to monitor quality during processing and storage (Kokini, 1985).

Since functional properties vary widely among the gums, a screening process is important to understand their potential food uses. Several factors become critical when selecting a gum. The most important of these is whether the functionalities of the gum meet the product's requirements (Dziezak, 1991). Blenford (1986) listed the factors for gum selection as shown in Table 10.

Conclusions

This article demonstrates that both nutritional and functional benefits can be derived from the use of dietary fibers in food products. This concept will enable food technologists to widen their opportunities for formulating fiber-enriched products (Andon, 1987). For the food industry to meet dietary fiber recommendation, there exists a need for cooperation among biomedical scientists, food scientists, food marketers and regulators to develop some sound strategies for integrating science, marketing and regulation (David Hurt and Crocco, 1986).

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