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COMPREHENSIVE REVIEWS IN FOOD SCIENCE AND FOOD SAFETY

Soluble Dietary Fiber

R. Chawla and G.R. Patil

ABSTRACT: Soluble dietary fibers (SDFs) are present in small quantities in almost each and every commodity and in combination with insoluble dietary fiber contribute towards total dietary fiber. The beneficial properties of SDFs have been associated with their significant role in human physiological function. Reductions in cholesterol level and blood pressure, prevention of gastrointestinal problems, protection against onset of several cancers, which include colorectal, prostate, and breast cancer, increased mineral bioavailability, and many more are the salient features of their potential. Some of the new unexplored soluble fibers are still under investigation for their use in a variety of commercial foodstuffs. This review outlines the various SDFs available, their major sources, and their potential functional role in human health.

Introduction

There is growing interest among consumers about the nutritional and therapeutic aspects of the food they eat. This has led to new inquiries about the linkage between food and health. The basic tendency of human beings has always been to procure and consume "natural foods". However, the fast pace of modern life has placed a great burden on such past activities and, consequently, canned, packaged, and ready-to-eat foods have now moved into a central position and onto the tables of modern consumers. Many of them have become aware that they are being deprived of some food components, which may be of immense importance to health. Milling of grain to white flour, ready-made squeezed juices, and many canned vegetables have clearly cut down the supply of fiber from the diet. Fiber not only increases the bulk of the food and moves it through the gastrointestinal tract more rapidly, but also helps in preventing constipation and possible colon and rectal cancer (Niness 1999a; Thomson 2005).

Prior to 1965, fiber was referred to as roughage, bulk, or ballast, and was measured as crude fiber. It is only in the past 25 to 30 y that fiber, now termed dietary fiber (DF), has been accorded the scientific importance it deserves. Intake of fiber through various foods such as nuts, whole-grain flour, fruits, and vegetables is now associated with decreased low-density lipoprotein (LDL)-cholesterol, lower insulin demand, increased stool bulk, softening of fecal contents, and improved laxative properties (Gordon 1989; Brown and others 1999a; Park and others 2005); and fiber has been associated with body weight regulation (Howarth and others 2001). Fiber increases mucin secretion for lubrication purposes and deficiency of fiber results in colonic mucosal fragility (Strugala and others 2003). Epidemiological studies have correlated high consumption of DF with lower incidence of certain diseases such as cardiovascular and cancer of colon and rectum. Such findings boosted searches for DF. Several conditions such as diabetes, atherosclerosis, breast cancer, diverticulitis, hemorrhoids have been connected to a low intake of fiber (Gutkoski and others 2007) and also the presence of obesity (Van Itallie 1978; Alfieri and others 1995). Fiber has now become the 3rd most sought-after health information in supermarkets in countries like India, Australia, Western Europe, and North America (Mehta 2005).

Useful knowledge about DF dates back to 1953 when Hipsley (1953) first discussed the meaning of DF. Accordingly, DF is a shorthand term for nondigestible constituents making up the plant cell wall. Since then, many definitions of DF have been advanced by several workers, including Asp and Johansson (1981) who developed methodology directed at quantifying food components. In 1985, Health and Welfare Canada defined DF as "the endogenous components of plant material in the diet which are resistant to digestion by enzymes produced by humans. They are predominantly nonstarch polysaccharides (NSPs) and lignin and may include, in addition, associated substances". A committee of the American Assn. of Cereal Chemists (AACC 1998) was charged to review and develop a definition of DF. Subsequently, in 2000, AACC defined DF as the edible parts 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 (Tungland and Meyer 2002). DF includes polysaccharides, oligosaccharides, lignin, and associated plant substances. DFs promote beneficial physiological effects including laxation, and/or blood cholesterol attenuation, and/or blood glucose attenuation (AACC 2000) (www.dietaryfiberfood.com/fiber-definition.php).

DF includes cellulose and lignin, hemicellulose, pectins, gums, and other polysaccharides and oligosaccharides associated with plants. It is now also defined as "edible parts of plants or analogous carbohydrates that are resistant to digestion and absorption in the small human intestine" (Mongeau 2003). DF is conventionally classified in 2 categories according to their water solubility: insoluble dietary fiber (IDF) such as cellulose, part of hemicellulose, and lignin; and soluble dietary fiber (SDF) such as pentosans, pectin, gums, and mucilage (Esposito and others 2005).

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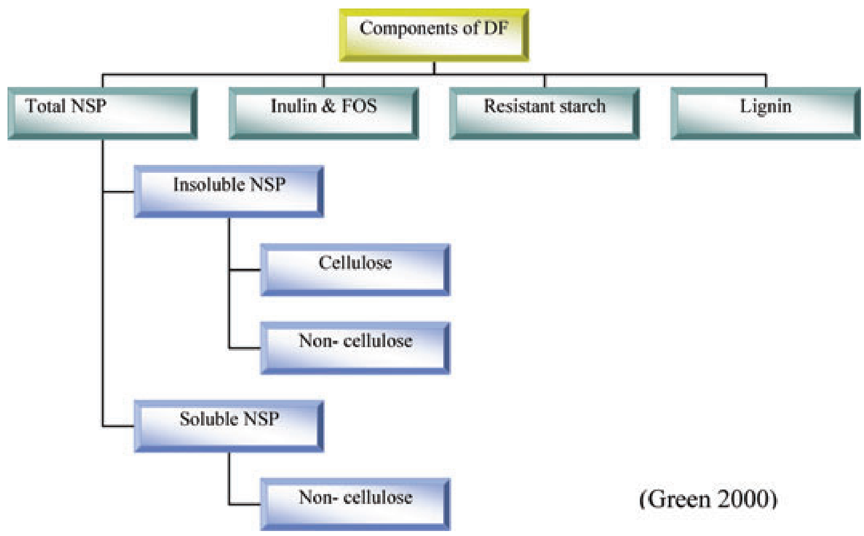

Figure 1 — Components of dietary fiber.

Table 1 — Dietary contribution towards fiber from different sources.

Fiber source	Noncellulose polysaccharides (%)	Cellulose (%)	Lignin (%)
Cereals	71-82	12-22	Tr*-15
Raw vegetables	52-76	23-42	Tr-13
Fruits	46-78	9-33	1-38

*Tr = Trace.
Source: Southgate (1969).

Components of DF (g/d)

DF can be divided into 4 main categories: total NSPs, which make up 11.8 to 16.4 g/d of total dietary fiber (TDF) intake. This part predominantly comes from cereals and vegetables, which contribute approximately 40% to 50% of the DF. Total NSPs can further be categorized into insoluble NSPs and soluble NSPs, which account for 6.5% to 7.0% and 5.3% to 8.7%, respectively. Apart from total NSPs, other different components are inulin and fructo-oligosaccharides (FOSs), resistant starch (RS), and lignin, which contribute 2% to 12%, 1.5% to 15%, and 1.0% to 1.4%, respectively, to our total intake of DF (approximately 16.3 to 43.4 g/d) (Figure 1). The contributions of these DFs from cereals, fruits, and vegetables are given in Table 1.

The energy provided by fiber varies in value from source to source, but the generally accepted and most frequently used value is 2 kcal/g (Wisker and Feldheim 1992).

System of Classification

DF can be classified by many possible ways such as on the basis of source that can be further categorized into plant polysaccharides, animal polysaccharides, and polysaccharides derived from native or synthetic sources. On the basis of structure, polysaccharides can be categorized into polysaccharides having linear or nonlinear molecular structure. On the basis of solubility they are soluble or nonsoluble. Other basic groupings are by properties, their applications, and on the basis of polysaccharide chemistry (BeMiller 2001). The classification of DF based on solubility is shown in Table 2.

Table 2 — Classification of food-ingredient polysaccharides based on solubility.

Class	Examples
Insoluble	Cellulose
Soluble only in hot water	Agars, algins (in the presence of Ca^{2+}), amyloses, kappa-type carrageenans (in the presence of K^{+} or Ca^{2+}), lambda-type carrageenans (in the presence of Ca^{2+}), furcellarans (in the presence of K^{+} or Ca^{2+}), gelan, konjac, mannan, locust bean gum, low-methoxyl (LM) pectins (in the presence of Ca^{2+}), granular starches, and starch derivatives.
Soluble in room temperature water, insoluble in hot water	Curdlan, hydroxypropylcelluloses, hydroxypropylmethylcelluloses, methylcelluloses.
Soluble in room temperature and hot water	Alginates (as Na^{+} salt), amylopectins, carboxymethylcelluloses, kappa-type carrageenans (as Na^{+} salt), lambda-type carrageenans (as Na^{+} salt), dextrins, iota-type carrageenans, dextrins, furcellarans (as Na^{+} salt), guar gum, gum arabic, gum tragacanth, high-methoxyl (HM) pectins, LM pectins (as Na^{+} salt), polydextrose, xanthan.

Source: BeMiller (2001).

IDF can be converted into SDF by chemical treatment, and this affects the sensory properties of the products. A newer approach is treatment of a cereal product with a tailored preparation of a *Trichoderma* enzyme (Napolitano and others 2006). The method has been proven successful and authors have validated that the typical method increases the SDF amount by 3 times its original amount without any marked decrease in TDF. The above treatment also causes the release of hydroxycinnamic acid, mainly ferulic acid that is linked to the polysaccharide chains. This is accompanied with an increase in the free phenolic concentration, water-soluble antioxidant activity, and bioavailability of the phenol compounds (Napolitano and others 2006).

Table 3—Different foodstuffs and their corresponding insoluble and soluble fiber contents.

Fiber source	Soluble dietary fiber g/100 g	Insoluble dietary fiber g/100 g	Total dietary fiber g/100 g	Reference
Wheat bran	4.6 ± 0.27	49.6 ± 0.59	54.2 ± 0.30	Claye and others 1996
Oat fiber	1.5 ± 0.01	73.6 ± 0.85	75.1 ± 0.86	
Rice bran	4.7 ± 0.12	46.7 ± 0.01	51.4 ± 0.11	
Apple fiber	13.9 ± 0.14	48.7 ± 0.13	62.6 ± 0.26	
Tomato fiber	8.3 ± 0.11	57.6 ± 0.43	65.9 ± 0.54	
Barley bran	3.0	67	70	Cho and Dreher 2001
Dried raw white beans	4.3	13.4	17.7	
Bread sticks	1.2	1.8	3.0	
Cooked rice	0	0.7	0.7	
Asparagus (cooked)	0.5	1.6	2.1	

Recommended Dietary Allowances (RDA) and Intakes

It is believed that a fiber intake of 30 to 40 g/d is desirable, one-half derived from cereal bran and the other half from fruits and vegetables (Nayak and others 2000). A range of foods is available, which are considered important sources of DF: grains and cereal foods, fruits, and vegetables, legumes, nuts, and seeds. Fruits and vegetables, being highly loaded with moisture, contribute less towards fiber, whereas grains are considered to be the richest sources of DF. For example, 1 cup of whole grain flour provides 13.2 g of DF/serving, whereas two-third cup of green peas provides only 7 g DF (Mehta and Kaur 1992). The amount of DF coming from cereal products differs to a great extent depending on the source and the processing of the item. For example, the content of DF in wheat flour varies from 2.5 g/100 g in refined flour to 12 g/100 g in unrefined flour obtained from whole wheat, in which most of the fiber consists of the insoluble fraction that otherwise gets lost during the refining process (Rodriguez and others 2006). The insoluble and soluble dietary fiber contents of different foodstuffs are given in Table 3. The isolated soluble fiber fraction ingested at high doses is unpalatable, giving a viscous mouthful and aftertaste. This effect can be reduced by fiber incorporation into solid foods. Low doses of the same when used as stabilizers and emulsifiers in food may have little or no taste effect.

The recommendations regarding the intake of DF are not the same in all countries. The United Kingdom proposes 18 g/d of DF expressed as NSPs, while an amount of 30 g/d has been proposed by Germany, and in the United States the specified intake should be 38 g/d for men and 26 g/d for women (BeMiller 2004). The DF intake ranges between 30 and 38 g/d for males whereas a value of 21 to 26 g/d has been proposed for females by Natl. Academy of Sciences, Food and Nutrition Board, U.S.A. (www.dietary-fiber.info/#recommendation). Similar information has been cited for the DF intake at (www.creationsmagazine.com/articles/C111/Boutenko.html) wherein the U.S. RDA for fiber is 30 g/d and an average American consumes between 10 and 15 grams of fiber per day. An average Indian diet contains about 6 to 8.5 g of crude fiber (Mehta and Kaur 1992).

Definition

At this point, one should know the clear-cut difference between the terms crude fiber **and** dietary fiber. The term DF refers to total amount of nondigestible material naturally occurring in foods and mainly of plant origin and it includes fiber from foods such as whole legumes, vegetables, fruits, seeds and nuts, undigested products, and undigested biosynthetic polysaccharides, whereas crude fiber is the material that in chemical analysis remains after vigorous treatment with acids and alkalies (Mehta and Kaur 1992). Fiber has gained much attention not only in adult diets but also in children meal plans (over the age of 3); thus, the American Health Foundation has recommended a consumption of 5 g plus child's age, in grams of fiber (Sloan 1995).

Physiological functions of SDF

Soluble fiber not only performs certain important physiological functions but also builds up important microflora by acting as a substrate food for beneficial microorganisms, therefore, it acts as a prebiotic and improves host health. A prebiotic aims selectively to feed probiotic organisms indigenous to the human colon (Shrivastva and Goyal 2007). Soluble fiber intake has been associated with protective effects against C-reactive protein (CRP), a marker of acute inflammation recognized as an independent predictor of future cardiovascular disease and diabetes. Thus, an inverse relationship has been found between DF intake and CRP concentration (Ma and others 2006). Also, research has indicated that fiber protects against inflammatory bowel diseases such as Crohn's disease and ulcerative colitis by increasing production of short-chain fatty acids (SCFAs), which act as immunomodulators in the inflamed intestine and also by increasing the proportions of beneficial rather than pathogenic bacteria that make up the gastrointestinal microflora (Galvez and others 2005). Most of the water-soluble fibers have hypocholesterolemic properties, possibly due to inhibition of fat digestion and absorption and inhibition of cholesterol synthesis in the liver by propionate or other bacterial products and the action of viscous NSPs on insulin and other hormone secretions (Truswell and Beynen 1992). The main effect of SDFs is associated with the viscous polysaccharides such as pectins and gums, which decrease the assimilation of nutrients. The bacterial mass that is formed from the high fermentable substances (pectins), the residues of the less fermentable polymers (cellulose and hemicelluloses) and the water retained by them are responsible for the increase of the fecal bulk (Madar and Odes 1990; Lefebvre and Thebaudin 2002). Prebiotics not only have physiological significance in human diets, they have also come to the attention of pet owners, pet food manufacturers, livestock producers, and feed manufacturers (Flickinger and Fahey 2002).

Although SDFs have little or no effect on carbohydrate metabolism, they have been found to reduce postprandial glucose excursions (Nayak and others 2000). Apart from this, these low-viscosity fibers are generally used by food processor and cooks to modify texture, rheology, and influence colligative properties of food systems and improve marketability of the food product as a health promoting or functional product (Sharma and others 2006). Each fiber fraction has an importance of its own, but when referred to in general, is included in the TDF content of a foodstuff. The objective of this article is, however, to emphasize the fractions of soluble fibers present in commodities, their importance, and their effects on physiological systems in human beings. A brief and concise summarization of selected soluble fibers is presented in Table 4.

Inulin and Oligofructose: Structure and Importance

Inulin-type fructans [β-(2,1)-fructans] extracted from chicory (*Cichorium intybus*) roots are prebiotic food ingredients, which in the gut lumen are fermented to lactic acid and SCFAs. Physically, inulin is colorless, odorless, and has a pleasant, slightly sweet taste with moderate solubility in water, dependent on temperature.

Table 4—Composition, occurrence, and effect of some selected soluble dietary fibers.

Name	Composition	Occurrence and production	Human physiological effects
Xanthan gum	β-1,4-D-glucose backbone, β-D-glucuronic acid, β-D mannose	Produced by fermentation using *Xanthomonas compestris*	Adds viscosity, fermented to short-chain fatty acids in human gut.
Carrageenan	Mixture of sulfated polysaccharides made up of α-D-galactose and 3,6-anhydro- -D-galactose	Extracted from red algae (Rhodophyceae)	Adds viscosity, decrease gastric emptying and small intestine transit time. Fermented in large intestine to short-chain fatty acids.
Agar	β-1,3-D-galactose and 3,6-anhydro-β-L-galactose	Extracted from red algae (Rhodophyceae; Gelidium spp. and Gracilaria spp.)	Adds viscosity, fermented to short-chain fatty acids in human gut.
Gellan gum	β-1,4-D-mannose backbone, β-D glucuronic acid, D-rhamnose	Produced by fermentation using *Pseudomonas elodea*	Adds viscosity, fermented to short-chain fatty acids in human gut.
Guar gum	Galactomannan residue	Produced by partial hydrolysis of guar gum	Fermented by colon microbiota, lipid lowering, lowering of plasma glucose.
Gum karaya	Acetylated galacturonic acid+ rhamnose+galactose	Dried exudates of the Indian tree *Sterculia urens*	Adds viscosity, fermented in human gut.
Gum tragacanth	Complex mixture of polymers of D-galacturonic acid, galactose, arabinose, xylose and cellulose	Dried exudates of Asiatic sp. of *Astragalua gummifer*	Adds viscosity, fermented in human gut.
Gum arabic	β-D-galactose backbone, L-arabinose, L-rhamnose, D-glucuronic acid	Dried exudates from stems and branches of African bush *Acacia senegal*	Fermented in human gut, prebiotic.
Alginate	β-1,4-D-mannuronic acid and α-1,4-L-guluronic acid	Extracted from brown algae (Phaeophyceae)	Adds viscosity, fermented in human gut.
Curdlan	β-1,3-D-glucose	Produced by fermentation using *Alcaligenes feacalis var. myxogenes*	Increased water-holding capacity.
Pectin	α-1,4-L-galacturonic acid backbone/ neutral sugar side chains, some ester groups	Fruits and vegetables (apple, citrus, sugar beet)	Decreases gastric emptying and small intestine transit time. Fermented in large intestine. No effects on stool weight, decrease in serum cholesterol.
Chitosan	2-amino-2-deoxy-β-D-glucose	By alkaline deacetylation of crustacean chitins	Increases fecal excretion of neutral steroids, intestinal absorption of cholesterol.
β –Glucan	β-1,4 D-glucose and β-1,3 D-glucose	Cereals (barley, oats)	Fermented in large intestine, strong butyrate production, lowers blood lipid.
Polydextrose	Mixed and random glycosidic linkages (1,6-bonds)-D-glucose	By vacuum thermal polymerization of glucose, sorbitol, and citric acid	Fermented to produce microbiota, short-chain fatty acid. Stool bulking and stool softening in intestine.
Xyloglucan	β-(1,4) linked D-glucose, partially substitutes with α-D-xylopyranose.	Extracted from seeds of *Tamarindus indica*	Fermented in the human colon. Adds viscosity in the small intestine.
Psyllium seed husk	Polymer of arabinoxylans with 1,4 and 1,3 linkages	Naturally occurring as husk of the psyllium seed	Reduced risk of coronary heart disease, reduced cholesterol.

Source: Sharma and others 2006.

Also, inulin comes under both soluble as well as insoluble fiber categories depending on the degree of polymerization (DP). Inulin and short-chain FOS are compounds with unique D-fructofuranose polymers linked by a $\beta 2 \rightarrow 1$ bond at the anomeric C_2 (Figure 2), and are accumulated in the tissues of many plant species (Delzenne 2003), with varying degrees of polymerization ranging from 2 to 60 (inulin) or 2 to 20 (oligofructose) (Gibson 1999). Native chicory inulin has an average DP of 10 to 20, whereas oligofructose contains chains with a DP of 2 to 10, and an average DP of 4 (Flamm and others 2001). Inulin is processed by food manufacturers to short-chain fructans by employing partial enzymatic (endoinulinase) hydrolysis, and long-chain fructans by applying industrial-scale physical separation techniques (De Leenheer 1996). Partial hydrolysis of inulin leads to a mixture of α-D-glucopyranosyl-[β-D-fructofuranosyl]n-1-D-fructofuranoside (GF_m) and β-D-fructopyranosyl-[β-D-fructofuranosyl]n-1-D-furanoside (F_m) type molecules. In chicory inulin, both GF_m and F_m compounds are considered to be included under the nomenclature of inulin and the number of fructose units varies from 2 to 70 (Figure 3).

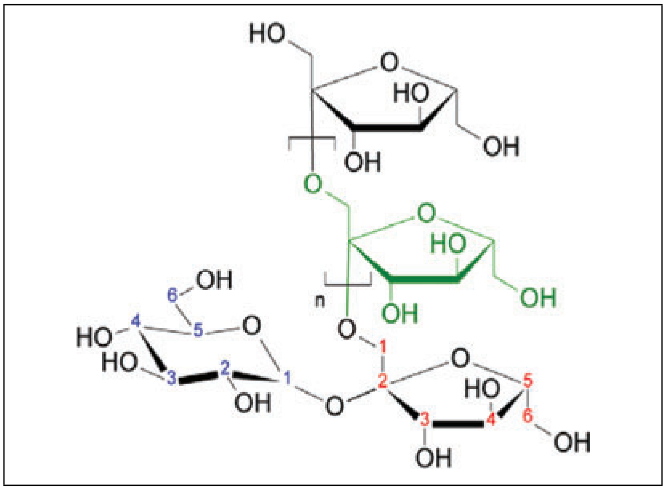

Figure 2—Structure of inulin.

Enzymatic synthesis from sucrose leads to GF_m molecules only. In the colon, they are rapidly fermented to produce hydrogen, methane, carbon dioxide, and short-chain carboxylic acids (acetate, butyrate, and propionate), lactate, and gases (Gibson and others 1995), along with SCFAs, which are good candidates to explain some of the systemic effects of inulin-type fructans. These SCFAs are absorbed and further metabolized in the coloncytes, the liver cells, or the peripheral tissues. Inulin and oligofructose are regarded as natural food ingredients and have been affirmed as generally regarded as safe (GRAS) (Kaur and Gupta 2002).

Role in human systems

Human data largely confirm reduction in blood triglycerides and cholesterol after administration of inulin and FOS. In an experiment employing response surface methodology (RSM) (RSM is a collection of statistical and mathematical techniques useful for developing, improving, and optimizing processes), it has been shown that cholesterol can be successfully removed in the presence of mannitol, inulin, and FOS using *Lactobacillus acidophilus*. Cholesterol removal patterns were observed over a 24-h period and highest cholesterol was removed from the medium containing inoculum size of 2.60% w/v; mannitol: 4.10% w/v; FOS: 3.30% w/v, and inulin 5.80% w/v. Of all the factors, FOS contributed significantly in the interaction pattern of mean doubling time, as well as higher growth rates (Liong and Shah 2005). Fiordaliso and others (1995) have shown that administration of oligofructose decreased total cholesterol levels in the blood serum of rats. It also protected against free cholesterol concentration, which could be induced by high-fat diets (Kok and others 1996). Research in experimental animal models has revealed that inulin-type fructans have anticarcinogenic activities. Also, evidence has been accumulated that shows that inulin-type fructans and corresponding fermentation products reduced the risk of colon cancer. The mechanisms involved included reduction of exposure to risk factors and suppression of tumor cell survival. Thus, this specific type of DF exerts both blocking agent and suppressing agent types of chemopreventive activities (Zobel 2005; Brown and Tuohy 2006). Yamashita and others (1984) have studied the effect of oligofructose intake on blood lipids and reported an 8% reduction in total and 10% in LDL-cholesterol after ingestion of 8 g of synthetic oligosaccharide for 14 d, compared with a control group receiving sucrose. Also, reduction was found more in case of hypercholesterolemic subjects. Various other studies have been summarized by Pereira and Gibson (2002) showing the effect of fructooligofructose on lipid metabolism. Nondigestible carbohydrates like inulin that pass through the digestive tract without being fermented or broken down reach the colon intact, where fermentation by bacteria takes place. Inulin has a low glycemic impact of 46 and a caloric value of 1.5 kcal/g (Ranhotra and others 1993; Mcdevitt-Pugh and Meyer 2005). Because of the properties like low glycemic response and management of weight and others, inulin also acts as a texturizer, thereby enhancing sensory properties, and is useful in low glycemic index recipes. Smooth energy bars and fast energy bars are products incorporating inulin. In fat-replacing applications, inulin provides what a basic fat replacer does not provide. Inulin acts as a rheology modifier and thus can optimize the texture of food systems and has been successfully utilized in cakes, sweet goods, bread, or other fermented products, and in icings (Silva 1996). Supplementation with inulin at 4% also improves utilization of intrinsic iron in the diet, as shown in a study by Yasuda and others (2006). Inulin-type fructans have been shown to improve the microbial balance of the intestinal ecosystem by stimulating the growth of bifidobacteria and lactobacilli, and by inducing changes of the intestinal mucosa characterized by higher villi, deeper crypts, increased number of goblet cells, and a thicker mucus layer on the colonic epithelium (Gibson and others 2005; Guarner 2007). Animal and human studies have shown that consumption of inulin and oligofructose increases the number of bifidobacteria

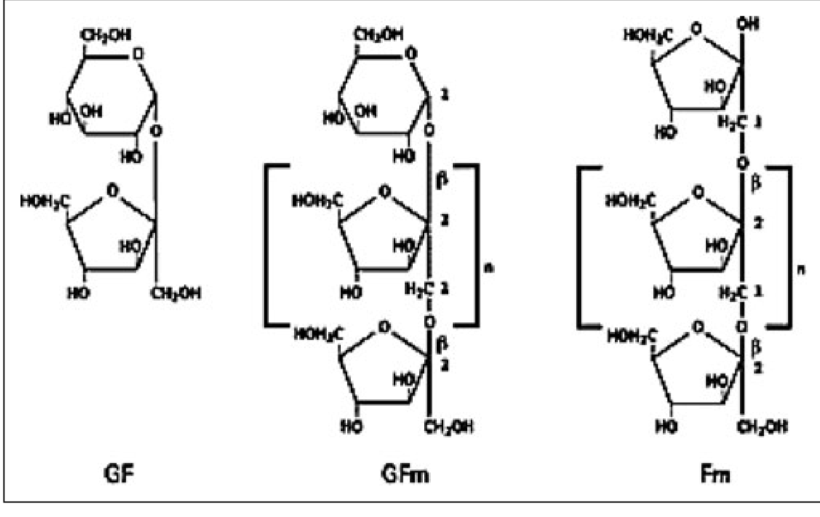

Figure 3—Chemical structures of sucrose (GF), and the fructans GF_m and F_m.

and lactobacilli in the mucosa, known as associated communities of the colon (Kleessen and others 2003; Langlands and others 2004; Bruggencate-Sandra and others 2006). The combination of inulin and bifidobacteria administration has been demonstrated to be an effective measure against several types of lesions and inflammations, not seen when either is administered separately (Guarner 2005). Administration of inulin and oligofructose has also been reported to reduce the occurrence of diseases such as colon cancer, breast cancer, osteoporosis, and heart diseases (Niness 1999b; Kaur and Gupta 2002). At present there are 2 approaches to prevent osteoporosis. The 1st is by optimizing bone mass acquisition in the skeleton during adolescent growth, the 2nd is by minimizing bone loss in postmenopausal period. Inulin and oligofructose might have a role in both. Increasing bone mineral density (BMD) and bone mineral content (BMC) with active mixture of inulin and oligofructose could maximize peak bone mass during adolescence thereby reducing skeletal fragility at later stage (Bosscher and others 2006). Similarly, inulin and FOS have also been found to reduce the activity of microbial enzymes involved in the production of toxins and carcinogens as well as reducing the concentration of these metabolites in feces (Burns and Rowland 2000).

Inulin and oligofructose are now being tested in human studies aimed at prevention of bacterial translocation in critical health conditions. Mixtures of probiotics and prebiotics, including inulin or oligofructose, have significantly reduced the rate of postoperative infections in liver transplant patients (Guarner 2007). Thus, inulin and oligofructose have proven useful to prevent mucosal inflammatory disorders in animal models and in patients with inflammatory bowel disease (Guarner 2007). It had previously been found that hepatocytes isolated from oligofructose-fed rats had a slightly lower capacity to synthesize triacylglycerol from radiolabeled acetate. This led to the hypothesis that decreased *de novo* lipogenesis in the liver through lipogenic enzymes is the key to reduction of very-low-density lipoprotein (VLDL)-triglyceride secretion in rats fed with oligosaccharides (Robertfroid and Delzenne 1998). Inulin has also been identified as a potential fiber in anticancer therapy with respect to potentiation of cancer chemotherapy in ascitic transplantable tumors bearing the NMRI strain (Taper and Robertfroid 2002). An acceptable daily intake (ADI) for inulin has been established up to 20 g (Coussement 1999). Animal and human studies have shown that consumption of inulin and oligofructose increases the number of bifidobacteria and lactobacilli in the mucosa-associated communities of the colon (Table 5) and hence, augments the effect of inulin and oligofructose effect on the proximal and distal colon flora (Guarner 2007). In the study, volunteers were fed a prebiotic mixture (7.5 g/d oligofructose plus 7.5 g/d of inulin) for 2 wk. Mucosal bacterial communities in biopsies from proximal and distal colon areas were characterized to species level and quantified. Thus, administration of inulin and oligofructose may improve the gut mucosal barrier and prevent gastrointestinal infections with enteric pathogens as well as systemic infections from translocation of gut bacteria (Kleessen and Blaut 2005).

Table 5—Effect of inulin–oligofructose on mucosa-associated flora.**

	Proximal colon		Distal colon	
	Control	Prebiotic	Control	Prebiotic
Total anaerobes	8.5 ±0.2	8.6 ± 0.2	8.7 ± 0.1	8.6 ± 0.1
Facultative anaerobes	6.4 ± 0.4	5.9 ± 0.4	6.4 ± 0.3	5.9 ± 0.3
Bifidobacteria	5.3 ± 0.4	6.3 ± 0.3*	5.2 ± 0.3	6.4 ± 0.3*
Eubacteria	4.5 ± 0.3	6.0 ± 0.4*	4.6 ± 0.3	6.1 ± 0.3*
Clostridia	5.1 ± 0.3	4.9 ± 0.3	5.0 ± 0.3	4.9 ± 0.3
Lactobacilli	3.0 ± 0.1	3.7 ± 0.2*	3.1 ± 0.1	8.6 ± 0.2*
Bacteroides	8.1 ± 0.3	8.3 ± 0.2	8.3 ± 0.2	8.5 ± 0.2
Enterobacteria	6.2 ± 0.4	5.6 ± 0.4	6.4 ± 0.3	5.9 ± 0.4

(*$P < 0.05$ vs. control).
Source: Guarner 2007.
**Data are logarithm counts of colony forming units per gram of tissue, expressed as mean and standard error.

Effect on mineral absorption

Human clinical studies have shown that inulin intake significantly increases the absorption of calcium (Niness 1999b) by altering the pH of the colon to enhance its absorptive efficiency (Izzo and Niness 2001). Active ingredients such as inulin and oligofructose are gaining more and more attention because they improve Ca absorption from the diet. Consumption of supplementary inulin and FOS also has a beneficial role on bioavailability of Ca and Mg (Ohta and others 1994; Coudray and others 1997, 2005; Morohashi and others 1998; Lopez and others 2000; Younes and others 2001; Griffin and others 2003). High absorption of Ca from the diet increases peak bone mass and, therefore, might postpone the risk of osteoporosis-induced fractures at older age (Bosscher and others 2006). In this regard, inulin and oligofructose play an important role in the prevention of osteoporosis. Similar findings have been reported by Abrams and others (2005) who stated that consumption of inulin and oligofructose in humans increases Ca absorption and improves both bone mineralization and BMD during periods of rapid growth.

Supplementation of standard formula with inulin increased Ca availability by 17.2% to 30%. However, availabilities of Ca, Zn, and Fe in milk infant formulas can be affected both positively and negatively by supplementation with SDF, as concluded by a study carried out to evaluate the effect of DF on mineral absorption from infant formula (Bosscher and others 2003). Some authors have reported that inulin and oligofructose enhance Ca absorption, while not influencing the balance of other minerals (Coudray and others 1997; Ellegard and others 1997; Scholz-Ahrens and others 1998; vanden Heuvel and others 1999). In ovari-ectomized rats, oligofructose increased BMC and impeded ovari-ectomy-induced loss of bone structure (Bosscher and others 2006). A study involving girls with high habitual Ca intake showed increased Ca absorption after supplementation of an oligofructose-enriched inulin (8g/d) in the diet (Bosscher and others 2006).

Oat Fiber (β-glucans)

Structurally β-glucans are comprised of β-(1,3) and β-(1,4) linkages (Figure 4), exhibiting distinct structural and physicochemical features (Napolitano and others 2006). They are mainly present in oats, barley, wheat, the cell wall of baker's yeast, certain types of fungi, and many kinds of mushrooms and bacteria. However, the highest values have been recorded in barley- and oat-based products (Plaami and Kumpulainen 1993). In wheat and barley, β-glucans constitute the most abundant NSP component of the endosperm cell wall accounting for approximately 3% to 4.5% of the total grain weight. Beta-glucans form long cylindrical molecules containing up to about 250000 glucose units. The presence of 2 types of linkages prevents the compact folding of β-glucan chains, making them soluble in water. Available data suggest their molecular weight ranges somewhere between 2.68×10^4 and 3×10^6 g/mol. The TDF in oats varies between 7.1% and 12.1%, the range attributed to differences in cultivars. The typical values for TDF, IDF, and SDF in oats are 18.6%, 10.6%, and 8.0%, respectively, as reported by Kahlon and Chow (1997). Wood and others (1989) processed oat grains

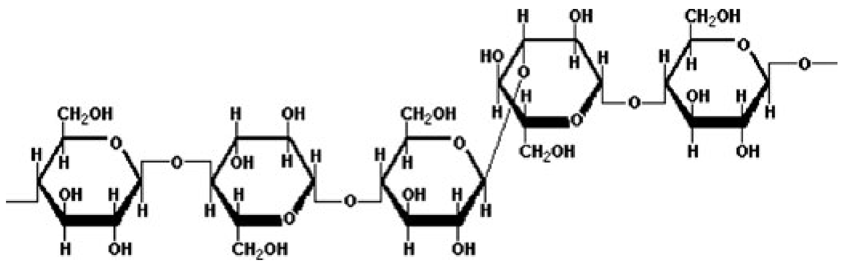

Figure 4 – Structure of β-glucan.

Table 6 – β-Glucan and dietary fiber contents (% dwb) of oat fractions obtained by air-classification and sieving.

Sample	Yield % of starting flour	β-Glucan	SDF	TDF
Dehulled Hinoat	–	4.7-5.7	5.4-5.8	12.7-14.2
Hexane-extracted, air-classified bran	38	11.2	Nd	Nd
Full-fat sieved, air-classified bran	34	12.8	14.3	37.5
Full-fat sieved bran	43	10.9	12.1	27.9
Ethanol sieved deactivated bran	21	16.6	18.8	40.1

Nd, not done.
Source: Wood and others 1989.

by refluxing with 70% to 75% ethanol to deactivate enzymes; the yields of bran and β-glucan are given in Table 6. Oat bran provides many health benefits including laxative properties, cholesterol reduction, absorption of prime minerals, and many more, but the most important one is reduction in serum cholesterol level (Anderson and Chen 1986; Malkki and others 1992; Behall and others 1997; Gerhardt and Gallo 1998; Kahlon and Woodruff 2003; Gebhardt and others 2004). The possible explanation behind the mechanism of cholesterol reduction is binding of bile acids in the intestine, thus more bile acids are lost when oat bran is eaten, and therefore, body cholesterol is used up to manufacture more bile acids.

Oat bran contains some insoluble fiber plus a larger amount of soluble fiber, both of which produce laxative effects. Oat fiber has also been shown to reduce postprandial glucose and insulin requirements (Braaten and others 1991; Ames and others 2006; Yokoyama and Shao 2006). An experiment conducted by Jenkins and others (1978) using oat and guar gum reported significant reductions likewise. Similar results have been reported by Makelainen and others (2007). The study conducted by Kim and others (2006) validated that overweight subjects require consumption of at least 2 g β-glucan per meal to reduce glycemic response, and a greater amount of β-glucan per meal may be required to achieve substantial effects in overweight subjects. The molecular weight of the β-glucan seems to play a role in its effect on steroid excretion and the decrease in plasma lipids (Pins and Kaur 2006). Oat grain differs from wheat in that it contains about twice as much polyunsaturated fat. Supplementation of β-glucan-enriched oat bran (20 g fiber) increases fecal concentration of butyric acid in patients suffering from ulcerative colitis and improvement was seen in them (Nyman 2003). Also, oat supplementation reduces the risk of coronary heart diseases (Truswell 2002; Berg and others 2003; Behall and Hallfrisch 2006), diabetic symptoms (Pick and others 1996; Tappy and others 1996), blood pressure (Kestin and others 1990; Saltzman and others 2001), and cancer incidence (Adom and Liu 2002) in humans and its health benefits have been proven and verified in countries like Sweden, the United States, and the United Kingdom (Duss 2004). Similar to inulin and oligofructose, consumption of oats decreases the absorption of Ca and Mg (Moak and others 1987), whereas according to other authors no significant differences in results have been reported (Bagheri and Gueguen 1981).

Salovaara and others (1991) formulated a product like yogurt and kefir based on oat bran. Bread and pasta made with incorporated barley as a source of β-glucans at 20% and 40% substitution against flour yielded lower calorie values as compared to control with 11% and 16%, and were acceptable sensorily (Knuckles and others 1997). A recent meta-analysis on lowering cholesterol levels suggested that soluble fibers (pectin, oat, guar gum, and psyllium) had a small but significant decreasing effect on total and LDL-cholesterol levels within a recommended intake range (Brown and others 1999b). Studies conducted using barley in the diet revealed that barley β-glucan has the potential to reduce total and LDL-cholesterol and improve glucose metabolism in different populations, thus is an effective option for improving lipids in moderately dyslipidemic men and women (Chen and others 2006; Pins and Kaur 2006). A study conducted by Queenan and others (2007) reported decreases in total and LDL-cholesterol with administration of 6 g β-glucan per day. The reduction in serum lipid risk factors for cardiovascular disease supports the Food and Drug Administration's (FDA) approval of a health claim for a DF intake of 4 servings/d (Anonymous 1997, 1998).

Oat β-glucans, though indigestible, are fermentable by bacteria in the colon. Thus they are prebiotics and also stimulate the sensation of satiety and help limiting appetite. The U.S. FDA has approved health claims for 2 DFs, β-glucan (0.75 g/serving) and psyllium (1.78 g/serving), in reducing cardiovascular disease risk (Jenkins and others 2002). Trogh and others (2005) prepared a SOLFIBREAD, which was fortified with barley β-glucan and wheat arabinoxylan soluble fiber, for health promoting effects. A relatively newer finding has discovered an insoluble fraction of β-glucan called curdlan, which derives this name owing to its property to get "curdled down" when heated. Curdlan, which possesses various functional properties (Jezequel 1998), is basically a β-1,3 glucan and consists of D-glucose monomers linked by β-glucosidic bonds at C_1 and C_3 to form a linear chain with no branching (Yotsuzuka 2001) (Figure 5). The uses of curdlan are confined to conventional food product preparations like to

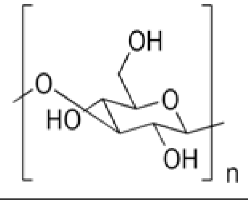

Figure 5 – Structure of curdlan.

processed meat and poultry products, batters and breadings, noodles, and surimi-based seafood, freeze-dried foods with improved rehydration time and texture, and various sauces and gravies. It is a fat replacer and texture modifier.

Polyfructan

A water-soluble fiber, synthesized from sucrose by the action of *Aspergillus sydowi conidia*, is a good source of SDF having much less viscosity than other polysaccharides. Polyfructan can be used in various bakery and dairy goods, in which it acts as a low-calorie bulking agent when used in conjunction with aspartame or other artificial sweeteners, or used as a fat substitute, such as in ice cream (Harada and others 1993).

Gums

The term "gum" is a descriptor based on physical characteristics and on the origin of the material in question. Gums have been described as water-soluble or dispersible vegetable exudates containing long-chain polysaccharides. They may be unbranched, significantly branched, or even covalently cross-linked, but they must interact significantly with water (Walker 1984). Supplementation of a diet with gums enhances its value by making the food dense without adding calories into it. Fibers with gel-forming properties are of particular interest in reducing elevated LDL-cholesterol without affecting the high-density lipoprotein (HDL)-cholesterol fraction, which has been validated by Smith (1987). As with other fibers, gums also exhibit hypocholesterolemic and hypotriglyceridemic effects.

Alginate

Alginate, a polyuronic saccharide (a hydrocolloid), can be isolated from the cell walls of number of brown seaweed species. It is also produced extracellularly by certain bacteria (Stokke and others 2000), comprising up to 40% of the total dry matter. Being from a family of unbranched binary copolymers, alginates consist of (1,4)-linked β-D-mannuronic acid (M) and α-D-guluronic acid residues of varying composition and sequence (Figure 6). Commercial alginates are produced mainly from *Laminaria hyperborean, Macrocystis pyrifera, Laminaria digitata, Acsophyllum nodosum, Laminaria japonica, Eclonia maxima, Lessonia nigrescens, Durvillea Antarctica, and Sargassum* spp. Alginate is widely used in the food industry as a stabilizer in bakery products, ice cream, cream, cake mixtures, frozen custards, and in beer manufacture (Brownlee and others 2005). Gelation in nearly all the gums takes place as a result of an ion-mediated interchain association. Gums enhance the foam and assist the suspension of fruit pulp in fruit drinks, which make the product more appealing to consumers (Neidleman 1991). The important feature of alginate is its gel-forming capacity in cold water. Several techniques may be used to prepare gels with algin, and the simplest among all is Ca diffusion into algin solution (Sanderson 1989). Regions of (guluronate monomers) G-blocks in one alginate molecule can be linked to a similar region in another alginate molecule by means of Ca ions or other multivalent cations. The divalent calcium cation, Ca^{2+}, fits into the guluronate block structure like eggs in an egg box. This binds the alginate polymers together by forming junction zones, resulting in gelation of the solution. Once formed, water molecules are physically trapped within the matrix by capillary forces yet remains free to migrate by diffusion, depending on size. This property can be utilized for immobilization or encapsulation (www.fmcbioploymer.com).

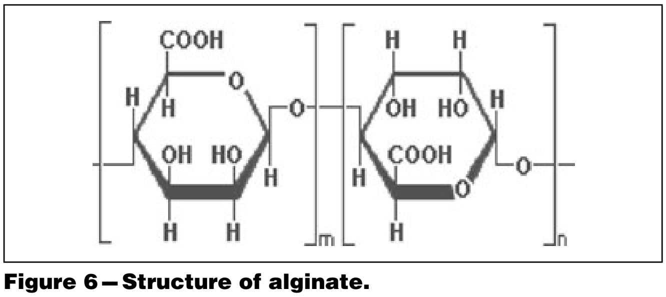

Figure 6 — Structure of alginate.

Intake of DF is generally accepted as being beneficial to both cardiovascular and colonic health, although a number of epidemiological studies have suggested that source and type of DF may be the more important modulators of colonic health and disease (Bonithon-Kopp and others 2000; Goodlad 2001; Levi and others 2001; Terry and others 2001). The alginate polymer can also be produced biologically employing *Azotobacter chroococcum* from whey degradation (Khanafari and Sepahei 2007). Effects of the thickeners alginic acid, locust bean gum, and guar gum on the availability of Ca, Fe, and Zn from casein-based and whey-based infant formulas were investigated by Bosscher and others (2001). They reported that addition of 0.42 g/100 mL locust bean gum reduced the availability of Ca from 21.2% to 9.4%, Fe from 0.48% to 0.32%, and Zn from 8.5% to 3.2%. In the whey-based formula, addition of 0.5 to 3.6 g/100 mL alginic acid, 0.14 to 1.44 g/100 mL locust bean, or 0.14 to 1.44 g/100 mL guar gum reduced Ca availability from 13.3% to 3.3% to 10.1%, 5% to 14%, and 7.7% to 11%, respectively. Guar and locust bean gums added at levels of 0.71% to 1.44 g/100 mL reduced Fe and Zn availabilities, whereas alginic acid increased Fe availability from 1.28% to 2.64% to 6.34% and Zn availability from 6.7% to 8.3% to 10.2%. Thus, it could be concluded that gums decrease the availability of some important nutrient minerals.

Carrageenan

Carrageenan is a generic term for several polysaccharides also extracted from seaweed. Carrageenan compounds differ from agar in that they have sulfate groups ($-OSO_3^-$) in place of some hydroxyl groups (Figure 7). Carrageenan is also used for thickening, suspending, and gelling food products. Gums including carrageenan can be used as a source of soluble fiber. They act as thickening or gelling agent and as a binder. Carrageenan is approved as a food additive in the EU with an ADI value of 75 mg/kg body weight and by The Food and Agriculture Organization (FAO)/World Health Organization (WHO) with a status of "not specified" (Nayak and others 2000).

Gum acacia

Gum acacia is a product derived from the exudates of acacia trees. It is a natural DF that is fermented in the large intestine and possesses water-soluble property along with benefits of its applications in emulsification and encapsulation. This gum has been identified as a complex mixture of complex carbohydrates with a molecular weight ranging between 2.5×10^5 and 1×10^6, containing small amounts (2%) of proteinaceous material and it has been categorized as an arabinogalactan–protein complex (Islam and others 1997). Diesol is a soluble fiber blend derived from several species of acacia trees. It is a light brown, free-flowing powder which provides a viscosity of 10 cps in a 5% solution that can be successfully added in high and light fiber drinks, soups, sauces, ice cream and other frozen desserts, dairy products such as yogurt, confectionery items such as snacks, bars, cheese cake, and more. Its fermentation has a prebiotic effect and produces SCFAs, which may promote several metabolic effects such as lowering of cholesterol (Kravtchenko 1997), increasing glucose

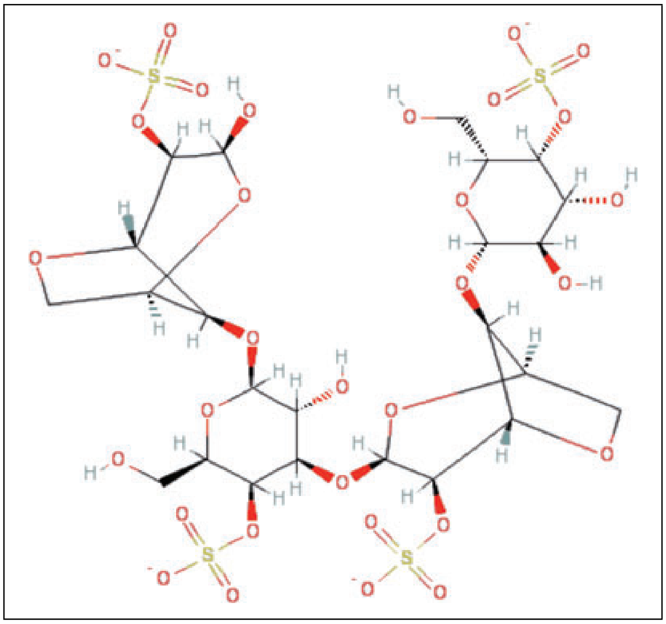

Figure 7 — Structure of carrageenan.

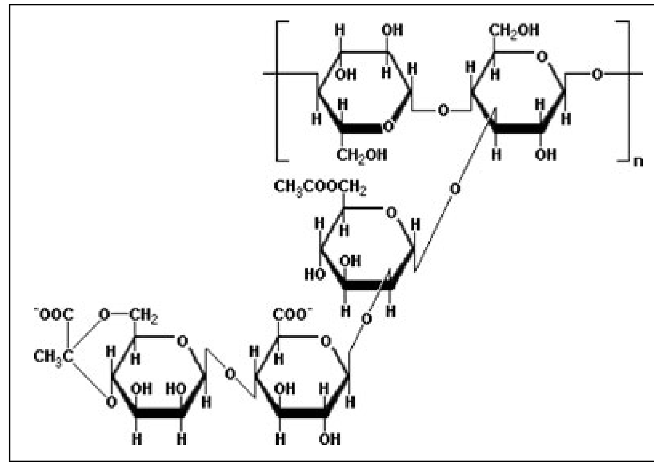

Figure 8 — Structure of xanthan gum.

tolerance, decreasing risks of heart disease and some types of cancer, and help improving bowel movement. Contrary to other low-viscosity soluble fibers, such as oligosaccharides, diesol does not exhibit laxative effects, which is attributed to its high molecular weight that does not disturb intraluminal osmotic pressure (www.diesol.com). It has also been validated that gum acacia carries the ability of reducing diarrhea, increasing stool weight, increasing N excretion, and also preventing renal tissue damage (Meance 2004). Gum acacia is also reported to be associated with low glycemic index (Castellani 2005).

Gum acacia has been considered an important contributor to overall economic sustainable development efforts in the Sahelian areas of Sub-Saharan Africa from which it is exported and its use is widespread in many foodstuffs worldwide (Meance and Lupein 2006). The same gum acts as a stabilizer and emulsifier in various beverage formulations (Benech 2005b; Pszczola 2005) and in various confectionery items owing to its benefits of low calorie contribution (Benech 2005a). Beverages with added gum acacia are reported to have health claims like binding of cations, improved absorption of sodium and potassium, cholesterol-lowering, and beneficial influence on digestive epithelium cells (Benech 2004). In wines, gum acacia has been reported to reduce astringency (Crespy 2004), and Thevenet (2003) reported a positive influence in the gastrointestinal tract when added in fruit juices and other foods and beverages. Bread prepared using gum acacia added at 0.1% or 0.2% resulted in maximized gas formation, gas retention, and bread softness (Sidhu and Bawa 2004). Use of gums has also been reported in the microencapsulation of flavors where it performs even better than starch (Reineccius and others 1995; Thevenet 1995). The same has been performed in confectionary also, as reported by Castro and Johnson (2007). In addition, acacia gum is also used in foods for its functional properties of emulsion stabilization and texturization.

Xanthan gum

This gum is a polysaccharide with a β-D-glucose backbone like cellulose, where every 2nd glucose unit is attached to a trisaccharide consisting of mannose, glucuronic acid, and mannose (Figure 8). Xanthan gum is commercially prepared by aerobic submerged fermentation from *Xanthomonas campestris* on cruciferous vegetables such as cabbage and cauliflower (Babbar and Jain 2006). Alternatively, xanthan gum can be produced from unmodified starches by *X. campestris* (Rosalam and England 2006) and molasses (Kalogiannis and others 2003). The negatively charged carboxyl groups on the side chains cause the molecules to form very viscous fluids when mixed with water. Hence, it can be used as a thickener for sauces and as a low-calorie substitute for fat in various recipes and also prevent ice crystal formation in ice cream. Xanthan gum is frequently mixed with guar gum because the viscosity of the combination is greater than when either one is used alone.

Xanthan gum can be used as prebiotic for lactic acid bacteria in milk. In related trials with respect to prebiotics, the gum had shown a protective effect on the viability of culture under conditions of low pH, refrigeration, and the presence of bile salts (Sadek and others 2006). Cakes prepared using xanthan gum were reported to have 50% to 60% reduced fat, allowing only 29.8% fat in the formulation with increased cake volume, and other internal and general characteristics similar to those of the general recipe product (Zambrano and others 2004, 2005). Such a reduced-fat yogurt ice cream has been reported by Hou and Du (2003). Mayonnaise prepared using guar gum and xanthan gum at 0.11% had physical and sensory properties similar to those of traditional mayonnaise, along with better stability during storage in mayonnaise with added gums (Lee and Song 2003). Various studies have been carried out with regard to emulsion stabilization with the addition of xanthan gum (Ramos and others 2004; Makri and Doxastakis 2006a, 2006b). A study carried out using different gums like hydroxypropyl methylcellulose (HPMC), guar gum, xanthan gum, and combinations of the latter 2 for deep-fat-frying purposes revealed that the porosity of the product (fried carrot slices) coated with batter containing guar and xanthan gums was about 3.6 times higher than the product coated with control batter, as gums are effective in controlling moisture loss and oil uptake, producing crisp and porous characteristics in deep-fat-fried products (fried carrot slices) (Akdeniz and others 2006). The same gums were found again better among all when used for deep-frying chicken nuggets (Sahin and others 2005). A low-fat ice cream using xanthan gum has been formulated with good acceptability (Maletto 2005).

A few soluble polysaccharides have also been reported to be associated with a potential to reduce hypercholesterolemic conditions and it has, therefore, been suggested that they could be used as ingredients in functional foods to reduce the risk of cardiovascular disease. However, the reverse results have also been reported as some studies indicated that addition of 1.5% hydrocolloids (xanthan gum and guar gum) to a cholesterol-free ration did not have any significant lowering effect on serum cholesterol profiles (Castro and others 2003). Bread manufactured using xanthan gum had larger loaf volume at 0.1% and 0.5% levels. Assessment of firmness using the Instron Universal Testing Machine (Model 4464, Instron Corp., Canton, Mass., U.S.A.) revealed bread samples to be significantly softer as a result of xanthan gum incorporation throughout the studied storage period (Singh and Bawa 2001).

Guar gum

Guar gum, a plant polysaccharide (made of the sugars galactose and mannose) and nonionic galactomannan, is isolated from the shrub *Cyamopsis tetragonolobus* that is traditionally cultivated for livestock feed. Its molecular weight ranges from 250000 to 2 million. Approximately 85% of guar gum is guaran, a water-soluble polysaccharide consisting of linear chains of mannose with $1\beta \rightarrow 4$ linkages to which galactose units are attached with $1\alpha \rightarrow 6$ linkages, where the ratio of galactose to mannose is 1 : 2 with 5 to 8 times the thickening power of starch (Figure 9).

This well-established gum is widely used in a variety of products, but suffers from off-flavor defect. To eliminate this existing problem, a newer technology (a proprietary manufacturing process that deodorizes guar gum without the use of organic solvents) has been developed by TIC Gums Inc. permitting its use in a range of specialty products and as an excellent source of SDF (80% minimum on an as-is basis and thus being odorless, this guar gum can be easily and profusely used in food materials (Ward 1999). Supplementing a diet with gel-forming fiber increases satiety, probably due to slower gastric emptying (Smith 1987). Guar gum powder can also be used as an emulsifier, to be added to sauces and salad dressings as a thickening additive, and to ice cream as an agent to prevent ice crystal formation. It can also be used as fat substitute that adds the typical fat-rich "mouthfeel" to various products. Consumers, however, are not very much aware of the use of guar gum powder as a stabilizer as the same also prevents the "weeping" of pastry by keeping it crispy. Guar gum also possesses the ability to alter postprandial lipid and lipoprotein composition, as in a study when test groups were fed with low-fiber as well as a high-fiber test meal. The results revealed that supplementation influenced postprandial glycemia, lipemia, and lipoprotein composition (Redard and others 1990), whereas another study, conducted by Groop and others (1993), indicated that the C-peptide response to a test meal increased in time during guar gum treatment, which indicates that insulin secretion is enhanced by guar gum as reflected by increased C-peptide, and it had long-term effects on glycemic control and lipid concentrations.

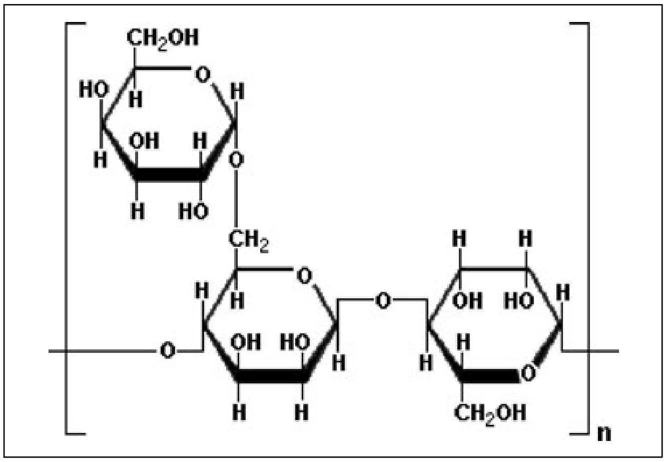

Figure 9—Structure of guar gum.

Table 7—Maximum permitted level of guar gum in various food products.

Product	Maximum level permitted (%)
Baked goods/baking mixes	0.35
Breakfast cereals, gravies, and sauces	1.2
Cheese	0.8
Dairy product analogs	1
Fats and oils	2
Jam and jellies	1
Milk products	0.6
Processed vegetables and processed juices	2
Soup and soup mixes	0.8
Sweet sauces, toppings, and syrups	1
All other food categories	0.5

Guar gum also increases absorption of Ca in totally gastrectomized rats (Hara and others 1999). Low doses have also shown low incidence of gastrointestinal side effects (Track and others 1985). A study carried out by Bortnowska and Makiewicz 2006 to evaluate the effect of xanthan gum, guar gum, and the mixture thereof on a model of low-fat mayonnaise in which 50% of oil was replaced by inulin, studied, and the results revealed that viscosity and adhesion increased with increasing concentrations of the gums and the highest being obtained when guar gum was added alone. McIvor and others (1985) validated that 30 g of guar gum per day has no serious consequences on the metabolism of human beings when consumed even for prolonged periods. The U.S. Code of Federal Regulations set maximum usage levels of guar gum permitted for specific products and these are tabulated in Table 7.

In a volunteer's study, hydrolyzed guar gum enriched diet (5 or 15 g) given for a period of 15 d, produced reduced serum cholesterol, free fatty acids, and glucose concentrations (Yamatoya and others 1997). A study carried out by Shahzadi and others (2007) to probe the effect of guar gum on serum lipid profile of Sprague Dawley rats wherein 3 different legume flours were mixed with commercial wheat flour (atta). The chapattis made thereof with 3 g/100 g of guar gum, when fed resulted in significant reduction in serum, LDL-cholesterol, and triglycerides. Effectiveness of guar gum in reducing the incidence of cardiovascular disease, diabetes, and obesity has also been demonstrated by Butt and others (2007). A study was carried out to assess effect of reduction in diarrhea incidence by soluble fiber in patients receiving total or supplemental enteral nutrition using randomized double-blind trial involving 100 patients fed with a standard diet compared with the same diet supplemented with 20 g of soluble fiber, containing partially hydrolyzed guar gum (Sunfiber), (per 1000 mL) by parenteral and enteral means. Thirty patients received total enteral nutrition postoperatively, and 70 patients received enteral supplementation. Results of the study indicated that the patients receiving total enteral nutrition with soluble fiber had decreased diarrhea but increased flatulence. In none of these patients did enteral feeding have to be discontinued because of gastrointestinal side effects, whereas in 4 patients, who were on a standard diet, enteral feeding had to be interrupted because of diarrhea ($P < 0.05$). Similar observations were made in patients

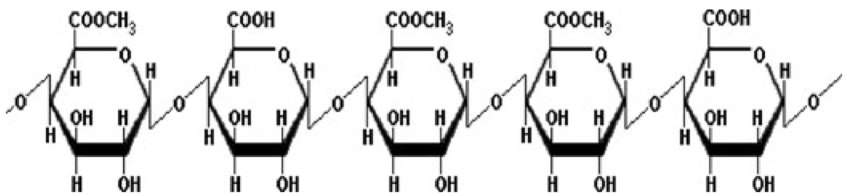

Figure 10—Structure of pectin molecule.

receiving enteral supplementation. In both groups, the incidence of diarrhea decreased significantly with the soluble fiber diet compared with the standard diet ($P < 0.05$) (Homann and others 1994). Guar gum has many advantages and is permitted for use in most processed foods, including dietetic foods, at a quantum satis level. The FAO/WHO (FAO/WHO 1975) estimates that the ADI for guar gum is "not limited." Also, reports indicate that guar gum possibly reduces the extent of absorption of nutrients such as glucose and amino acids. However, there is no evidence to indicate that the bioavailability of micronutrients is influenced significantly (Todd and others 1990; Groop 1997).

Pectin

Pectin is a polysaccharide that acts as a cementing material in the cell walls of all plant tissues. It is the methylated ester of polygalacturonic acid, structurally composed of chains of 300 to 1000 galacturonic acid moieties, plus neutral sugars such as L-rhamnose, D-galactose, and L-arabinose units joined together to form a linear chain with $1\alpha \rightarrow 4$ linkages (Figure 10) (Fernandez 2001). The degree of esterification (DE) affects the gelling properties of pectin. The white portion of the rind of lemons and oranges contains approximately 30% pectin.

In a study carried out by Singh and others (2005) various hydrocolloids like carrageenan, carboxymethyl cellulose (CMC), pectin, and guar gum at 0.1% and 0.25% were used to improve the thermal stability and aesthetic quality of whey protein in whey-based beverage systems. The stabilizing effects of the stabilizer showed a progressive increase with an increase in the level of its addition from 0.1% to 0.2%, but among CMC, guar gum, carrageenan, and pectin, at 0.25% carrageenan and pectin showed maximum stability. Pectin administration has also shown beneficial results in response to postprandial glycemia and serum insulin levels which is because of addition of natural or chemically processed fiber which has been shown to decrease both the postprandial and fasting blood glucose in type-2 diabetics by delaying carbohydrate absorption. A study involving addition of guar flour or pectin, or both in the diet showed reduction in postprandial glycemia and serum insulin, wherein a liquid test meal was when fed to 4 subjects showed reduction in blood glucose after an interval of 30 min from 6.33 ± 0.19 mmol/L to 4.77 ± 0.17 mmol/L by addition of guar gum ($P < 0.05$). The mean insulin level was also significantly lower at 15 min. A similar meal in which guar was added to the bread and pectin to the marmalade resulted in significant reductions of blood glucose at 15 min ($P < 0.002$) and 30 min ($P < 0.01$) (Jenkins and others 1977). For every 1 g of pectin added to the diet, stool weights were found to increase by 1.3 g (Cummings 1986). In addition to changing the morphology, a pectin-incorporated diet also caused increased crypt cell mitotic activity, while the same decreased when oat was supplemented in the diet (Jacobs 1983). Processing of foods containing DF leads to degradation of insoluble fiber; and the distribution between soluble and insoluble fiber content also gets modified. At lower concentration (100 mM) of $CaCl_2$, redistribution of SDF to IDF as the result of cross-linking of pectin molecules occurs, but at higher concentrations (400 mM), pectin is fully degraded with considerable loss of both soluble and insoluble dietary fiber (Nyman 2003). The possible explanation for this phenomenon given by authors is depolymerization and breaking of glycosidic linkages during heating (Nyman and others 1994); thus the molecular weight of soluble fiber was observed to be highest in raw carrots, followed by blanched, and was the least in boiled carrots (Svanberg and others 1995). The lower molecular weight of soluble fiber also results in lower viscosity. Doubling the molecular weight has been suggested to increase the viscosity by factor of 10 (Eastwood and Morris 1992).

Pectin has been reported to be associated with the absorption of ^{65}Zn and reported to significantly reduce liver cholesterol concentrations (Sungchan 1994). Hoersten and others (1991) reported on a beverage fortified with pectin (0.2% to 1.2 by wt.%) with good acceptability. Low-fat shortbread cookies were made using gum arabic, pectin, or CMC to replace 25%, 50%, or 75% of shortening fats. Cookies made with 25% or 50% pectin or 25% gum arabic had the highest quality attributes in terms of taste, color, and overall acceptability (Salama 2001). Dietary pectin levels ranging from 10 to 36 g/d did not alter the balance of Ca, Mg, P, or Zn (Cummings and others 1979; Sandberg and others 1983). A study carried out by Galibois and others (1994) on rats to determine mineral absorption using pectin, cellulose, and oat and wheat fiber found that the apparent absorption of Zn, Fe, Mg, and Ca was better with pectin than with wheat or oat bran. Many studies have been conducted to determine the effect of pectin on vitamin absorption, but they have not yielded any conclusive results so far (Fernandez 2001).

Apple fiber

Apple fiber, a soluble type of fiber, is rich in pectin. Soluble or gel-forming fibers absorb water from the digestive tract. This helps to increase the size of the stool and normalize its transit time through the bowel. Soluble fiber can be beneficial in cases of constipation and diarrhea. Having adequate fiber in the diet may also have a protective effect against diverticulosis, colon cancer, hemorrhoids, and varicose veins. Studies have shown that apple fiber, when used as part of a calorie-controlled diet, can enhance weight loss. Similarly, a study conducted to visualize the effect of apple fiber on lowering of increased plasma and liver cholesterol, it was found that apple fiber or pectin substantially reduces the same when fed at 2.5% or 5% in the diet (Wells and Ershoff 1961). Apple fiber has a mild appetite suppressing effect by producing a sense of fullness; it also improves the process of digestion and elimination by stimulating healthy bowel functioning. The pectin in apple fiber helps to normalize the levels of fats in the blood stream. Research has shown that apple fiber taken each day can have the effect of reducing total cholesterol up to 10% in people with elevated cholesterol levels (http://au.health.yahoo.com/041101/25/1uk9.html?r=967673075). Processing (autoclaving) apples reduces TDF and IDF, as reported by Chang and Morris (1990), but of course the decrease in the content is dependent on the type of fiber and processing method employed.

Psyllium husk. The seed husks of psyllium (*Plantago ovata* Forsk) have a long history in that they have been used since time immemorial. Uses of psyllium include regulation of large bowel function and promotion in laxation by its presence in the intestine. A study has been conducted and validated that each gram of psyllium seed husk increases human stool weight by an average of 5.9 g, compared with 4.9 to 5.4 g for wheat bran fiber and 3.4 to 4.5 g for oat bran fiber (Stephen and Cummings 1980; Cummings 1993; Chen and others 1998). The use of psyllium used to be restricted to elderly patients who benefitted from its laxative effect, but later studies pointed out that psyllium can be successfully used for the treatment of hypercholesterolemia and total blood cholesterol and LDL-cholesterol control (Anderson and others 1988; Anderson 1995; Anderson and others 2000). The exact mechanism is not known, but it is assumed to be due to stimulation of bile acid synthesis that further reduces LDL-cholesterol (Everson and others 1992). A study conducted by Wolever and Jenkins (1994) has revealed that it is not only psyllium that plays an important role in lowering blood cholesterol, but other components of a meal also jointly affect the same, as in a study in which psyllium was included in breakfast and significantly reduced the blood cholesterol level, whereas the same fiber had no effect when taken between the meals, which suggests its interaction with other food constituents. Psyllium, because of its low fermentability, is the only soluble fiber that appears to inhibit tumor formation (Roberts-Anderson and others 1987) and to reduce chances of contacting colon cancer (Malhotra 1977; Segal and others 1995). The proposed mechanism involves ingestion of prebiotics (nondigestible food ingredient that selectively stimulates bacteria in the colon) that results in a different spectrum of fermentation products, including the production of high concentrations of SCFAs, leading to a decrease in pH. A low pH in feces is associated with a reduced incidence of colon cancer in various populations.

Being considered a good source of SDF, among others, psyllium can be added into various breakfast dishes to aid in cholesterol management. A recently conducted study has identified a gel-forming polysaccharide in psyllium mucilage as neutral arabinoxylan (Fischer and others 2004). Cookies containing psyllium have been prepared using a combination of 3 to 15 wt% water and/or fresh eggs with 0.6 to 35 wt% dry ingredients (sugar, flour, nonpregelatinized starch, egg solids, protein solids or their mixtures); incorporating 10% to 35% fluid shortening (specifically a polyol ester, for example, sucrose octaoleate or octastereate) and combining the resultant mixture with 5 to 30 wt% psyllium plus other conventional cookie components. The cookies prepared thereof were intended particularly for treating gastrointestinal disorders and reducing blood cholesterol levels (Pflaumer and others 1990). In another study, male Hartley guinea pigs were fed semipurified diets containing various levels of psyllium and cholesterol to determine mechanisms by which psyllium lowers plasma LDL concentrations and found that secretion of smaller VLDL particles and metabolic alterations contribute to lowering of plasma LDL cholesterol levels (Fernandez and others 1995). Results indicated that consuming a psyllium-enriched cereal as a part of a low-fat diet improves the blood lipid profile of hypercholesterolemic adults (Beth-Olson and others 1997).

Methylcellulose (MC) and HPMC. These gums possess unique and unusual properties and are not measured along with total (insoluble and soluble) dietary fiber, attributed somewhat to unusual solubility and also to certain unknown factors. These gums have been successfully used as food additives without any adverse effect (McCollister and others 1973; Nitschke and Fiero 1977; Santos and Expert Panel 1986). MC has attained GRAS status and has been widely used in food/industrial applications. Kinnow mandarin squash prepared using added CMC, guar gum, pectin, sodium alginate, agarose, gum ghatti, and gum tragacanth was stored for 6 mo and CMC showed best results among all in terms of overall acceptability (Aggarwal and Sandhu 2004). CMC has also been reported to be associated with absorption of ^{65}Zn (Sungchan 1994).

Resistant Starch

By definition, RS is that portion of the starch, which is not broken down by human enzymes in the small intestine. It enters the large intestine where it is partially or wholly fermented. The fermentation products are mainly SCFAs or volatile fatty acids (VFAs), methane (CH_4), hydrogen (H_2), and carbon dioxide (CO_2). The SCFAs produced from the fermentation are absorbed at site of production and transported to the liver via enterohepatic circulation. It was 1st reported by Englyst and others (1982) (www.megazyme.com/booklets/KRSTAR.pdf) and the elaboration of the same work was taken up by Berry (1986). These types of starches, which escape small intestinal absorption may contribute to fecal bulk (Phillips and others 1995; Behall and Howe 1996) alter the colonic microflora, increase fecal nitrogen losses, and SCFA synthesis, especially butyrate (Silvester and others 1995) and possibly reduce the risk of colon cancer (Cassidy and others 1994). (For more details on RSs, readers are suggested to read articles published in *CRFCS* [Vol. 5, 2006] and *Nutrition Research Reviews* [Vol. 16, Issue 2, 2003].)

A study conducted using 2 different types of RSs (One starch was a high-amylose granular resistant cornstarch (RS2), and the other was a high-amylose nongranular, dispersed, and retrograded resistant cornstarch (RS3), to assess the effect on fecal bulking, fecal SCFA production, blood lipids, and glycemic indices. The supplements were a low-fiber (control) and supplements providing an additional 30 g DF as wheat bran (high-fiber control). Fecal and 12-h breath gas collections were carried out and results indicated that wheat bran supplement increased fecal bulk (96 ± 14 g/d) compared with the low-fiber control with the mean for both RSs also being greater (22 ± 8 g/d) than the low-fiber control. Similarly, the mean fecal butyrate and SCFAs ratio also had positive implications for colonic health (Jenkins and others 1998). The major physiological effect of RSs therefore appeared to be as substrate for colonic fermentation with a modest fecal bulking activity. Storage increases the amount of RS as validated by a study conducted by Namratha and others (2002), who prepared and stored various ready-to-eat food products developed by the Defence Food Research Laboratory (DFRL) in Mysore. Before storage, RS contents averaged 4.2% to 25.6% of total starch, which increased to 6.6% to 36.9% after storage of 4 mo.

In another study, effect of long-term feeding of RS was evaluated and results indicated that long-term ingestion of RS induces pronounced adaptation of the gastrointestinal tract and microflora to starch fermentation and the same was associated with beneficial effects for gastrointestinal health in terms of microbial phylogenetic profile, increased butyrate production, and modified mineral absorption and colonic morphology (Martinez-Puig and others 2007). Effect of RSs on insulin sensitivity and tissue metabolism was studied by Robertson and others (2005), wherein euglycemic–hyperinsulinemic clamp and insulin sensitivity was higher after RS supplementation than after placebo treatment (9.7 and 8.5 × 10^{-2} mg glucose per kg min), respectively, along with lower release of subcutaneous abdominal adipose tissue, nonesterified fatty acids, and glycerol. The authors from the study concluded that dietary supplementation with RS has the potential to improve insulin sensitivity. Consumption of RSs also improves postprandial plasma glucose and insulin levels in women when consumed along with β-glucan was proved by a study carried out by Behall and others (2006), where 10 normal-weight (43.5 y of age, BMI 22.0 kg/m^2) and 10 overweight women (43.3 y of age, BMI 30.4 kg/m^2)

Table 8—Chemical structure of lignin monomeric units.

X	R_1	R_2	Common name	Chemical name of substituent
$-CH_2OH$	H	H	Hydroxyphenyl	4-Hydroxyphenyl-
	H	OCH_3	Guaiacyl	3-Methoxy-4-hydroxyphenyl-
	OH	OCH_3	5-Hydroxyguaiacyl	3-Methoxy-4,5-dihydroxyphenyl-
	OCH_3	OCH_3	Syringyl	3,5-Dimethoxy-4-hydroxyphenyl-
$-COOH$	H	H	ρ-Coumaric	4-Hydroxyphenyl-
	H	OCH_3	Ferulic	3-Methoxy-4-hydroxyphenyl-
	OCH_3	OCH_3	Sinapic	3-Methoxy-4,5-dihydroxyphenyl-

Source: Monties 1989.

consumed 10 tolerance meals in a Latin square design. Meals consisted of (1 g carbohydrate/kg body wt) glucose alone or muffins made with different levels of soluble fiber (0.26, 0.68, or 2.3 g β-glucan/100 g muffin) and 3 levels of RS (0.71, 2.57, or 5.06 g/100 g muffin). Results indicated that overweight subjects had higher plasma insulin concentrations than those of normal-weight subjects but maintained similar plasma glucose levels. Compared with low β-glucan–low RS muffins, glucose and insulin area under curve (AUC) decreased when β-glucan (17% and 33%, respectively) or RS (24% and 38%, respectively) content was increased. The greatest AUC reduction occurred after meals containing both high β-glucan high RS (33% and 59% lower AUC for glucose and insulin, respectively). The authors concluded that soluble fiber appears to have a greater effect on postprandial insulin response while glucose reduction is greater after RS from high-amylose cornstarch. The reduction in glycemic response was enhanced by combining RS and soluble fiber.

Lignin

Lignin is, next to cellulose, the most abundant renewable resource and worldwide about 50 million tons of lignin is being produced annually as residue in paper production processes (www.biomassandbioenergy.nl). Lignin is the only substance which is a noncarbohydrate type of DF and forms largely the woody parts of plants, and is a high-molecular-weight aromatic polymer formed by enzymatic dehydrogenation and subsequent polymerization of phenylpropanoids composed of monomeric units shown in Table 8. A complete structure of lignin is not well defined because the lignin structure itself differs between various plant species. Although a precise structure for "intact" lignin has not been determined, general models have been proposed and one such is shown in Figure 11. Lignin stiffens the cell wall and serves to enmesh the various polymers in the wall (MacDougall and Selvendran 2001). In the intestine, it combines with bile acids to form insoluble compounds, thus preventing their absorption (Rodwell 1990). NSPs clearly affect bowel habit and so, to a lesser extent, does RS. Feeding some NSPs reduces blood cholesterol concentration in humans as well as in experimental animals (Aro and others 1984; McIvor and others 1986; Anderson and others 1991; Nishina and others 1991; Gumaa and others 2001).

Sources of lignin

Lignin is consumed in small quantities because of its association with spiral and annular bands in xylem conducting vessels. Also, as the woody tissues are not frequently consumed, its comparative consumption is less (Southgate 1993). Lignin is abundantly present in "whole" preparations and also in fruits that contain edible seeds and mature vegetables such as carrots and other root vegetables (Salvin 1987). In general, lignin value increases with increasing amounts of NSP (Flint and Camire 1992). Lignin content of various commodities is presented in Table 9.

Importance of lignin in human diet

Lignin is thought to act as a physical barrier to microbes, limiting their capacity to fermentation (Jung and Allen 1995). A study was carried out to determine the effects of isolated lignin and intact lignin in foods on bioavailability of intrinsic iron and of supplemental iron ($FeSO_4{\cdot}H_2O$) wherein standard curve and slope ratio methodology were employed to determine the effect of the same. Results of the study revealed that the presence of lignin decreases the bioavailability but not to a significant extent (Fly and others 1998). Purified lignin has also been shown to reduce protein digestibility in rats (Shah and others 1982) and in mice (Keim and Kies 1979), although the effect was negligible. Similarly, to assess the effect of lignin on growth performance and blood metabolites employing 32 piglets, lignin-enriched diet was offered for 4 wk. The results of the study indicated that lignin supplementation had a hypolipemic but not hypocholesterolemic effect (Valencia and Chavez 1997). Dietary lignin has also been reported as a precursor of mammalian lignans, which are phytoestrogens and may contribute to the prevention of breast cancer and coronary heart disease. Also, the mammalian lignans, enterolactone, and enterodiol, commonly found in human plasma and urine, are formed by the conversion of dietary precursors such as secoisolariciresinol and matairesinol lignans by the colonic microflora (Begum and others 2004). Lignins on their positive side have also been reported to have a role in the anticancer treatment as it induces apoptosis via production of an ascorbyl radical in the presence of vitamin C (Sakagami and Satoh 1996) along with their beneficial role in lipid balance. The affinity of lignin polymers for phenolics has also been suggested as the mechanisms for the reducing effect of colon cancer (Ferguson and Harris 1996).

Characterization of DF lignins from different fruits and vegetables was done using the derivatization followed by reductive cleavage (DFRC) methodology. To enrich lignin contents and to minimize polysaccharide excess that could lead to nonanalysable DFRC chromatograms, the insoluble fibers were degraded by a carbohydrase mixture. The residues that were found were representative for the insoluble fiber lignins and were analyzed. The investigated fibers differed considerably in their lignin contents and also in their lignin compositions. Lignins noticeably differed in the ratio of the DFRC products resulting from syringyl units (S) and guaiacyl (G) units (G/S ratios ranged from approximately 39 to 0.2) (Bunzel and others 2005).

Analytical approach to determination. Various methods have been reported by research workers for the determination of fiber content in foods. The 1st method was reported by Weende that consists a sequential extraction of fiber with dilute acid and alkali solutions, and was adopted till 1960s. Afterwards different methods were employed for the estimation of TDF in foods, including "acid detergent fiber" (ADF), enzymatic determination (the Prosky method), which is a time-consuming process (Prosky and others 1992; Mongeau and Brassard 1993). However, recently Tada and Innami (2007) modified the same using newly available enzymes.

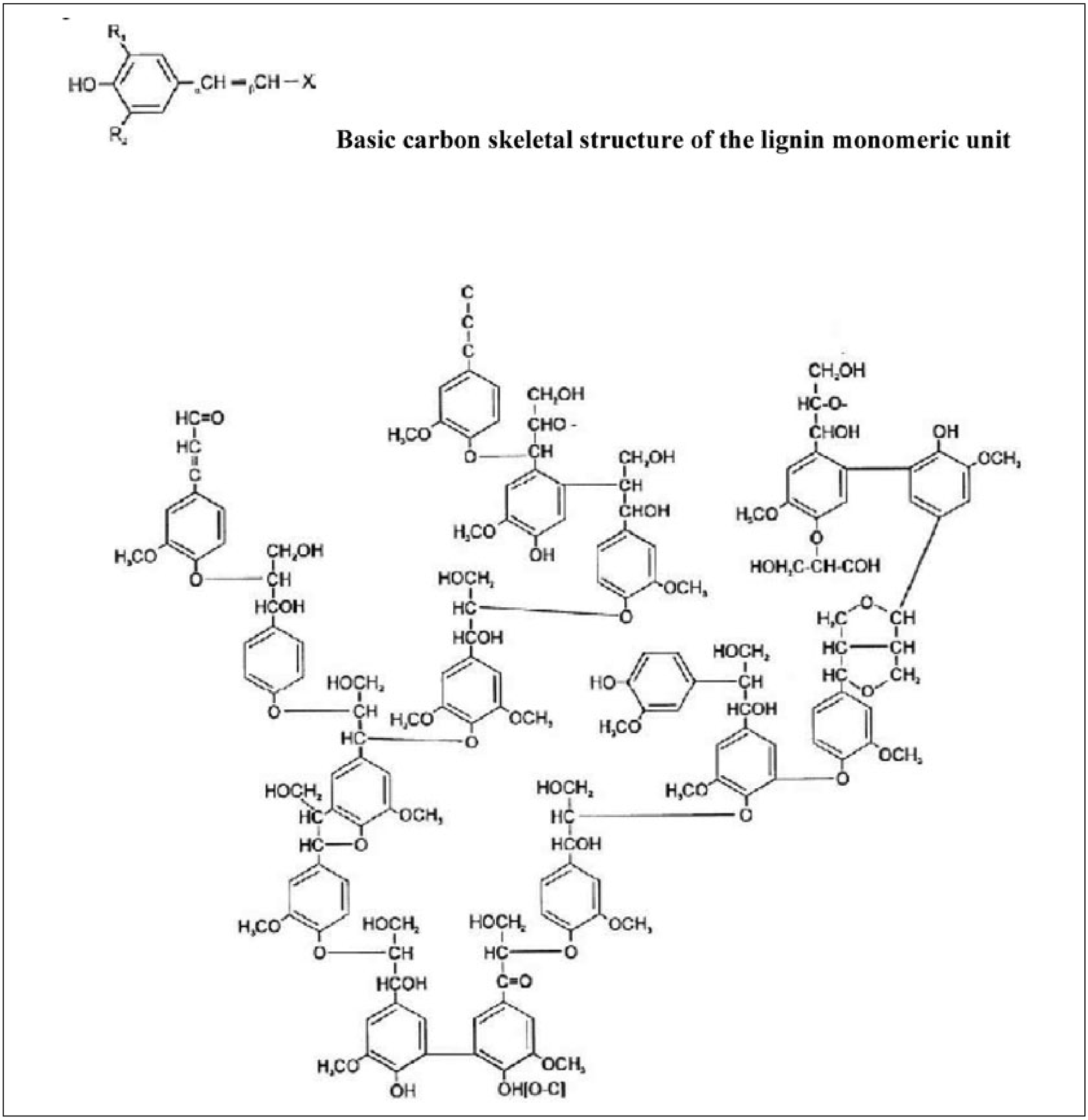

Figure 11 – Proposed partial structural model of spruce wood lignin molecule.

Gums, specifically gum acacia, can be analyzed using advanced technologies like electrophoresis, and the 1st attempt in this was made by Lewis and Smith (1957). A further advanced methodology has been recommended by Motlagh and others (2006) to separate high-molecular-weight glycoprotein from polysaccharide components and further separation of low-molecular-weight protein ranging from 2×10^3- 2×10^5 Da. Also, gums can be estimated using colorimetric techniques. Of the colorimetric methods available for quantification of CMC, the 2,7-naphthalenediol method (NDM) is the most specific one (Zorba and Ova 1999). An advanced and sophisticated method of estimation of methyl and HPMC has been recommended by Harfmann and others (2007) whereas a modification to the AOAC procedure with size-exclusion chromatography for their determination was published by Turowski and others (2007).

Different research workers have carried out analyses to determine DF with little modifications, and these are available for use: Southgate approach, Englyst modifications (Englyst and

Table 9—Different products and their corresponding lignin content.

Food category	Products	g lignin/ 100 g food
Pasta	Spaghetti and macaroni, cooked (exclude whole wheat)	0.35
Rice	Rice, medium grain, regular, cooked and white rice	0.35
Cookies	Cookies, ginger snaps, and plain	0.20
Other breakfast cereal	Mix of corn flakes, Cream of Wheat, Frosted Mini Wheats, Grape-Nuts, Puffed Rice, Rice Krispies	0.48
Citrus fruits	Average of oranges and grapefruit and lemon	0.33
Whole grain, oats, and high fiber cereals	Mix of 100% Branflakes, 40% Branflakes, All Bran, Bran buds, Alpen, Bran flakes, Corn bran, Wheaties, Shredded Wheat	1.69

Source: Mongeau and Brooks 2001.

Cummings 1990), Theander and Westerlund analytical scheme, Mongeau and Brassard method, and the recent advancement with the least chances of error, include—near infrared reflectance spectroscopy (NIRS), pioneered by Norris and Baker (Hall 1989). The most recent method of DF determination includes liquid chromatography (Ohkuma and others 2000). Kitada and others (1997) determined SDF using electrophoresis, high-performance liquid chromatography (HPLC), and size exclusion chromatography (Turowski and others 2007) with refractive index detector (Harfmann and others 2007). Haines and Patel (2003) employed ELISA for the determination of soluble fiber.

There are some methods, which involve measuring NSP alone (Englyst and Hudson 1996), but they give lower estimates than methods for TDF in foods containing RS, resistant oligosaccharides, and/or lignin. Several methods exist to analyze lignin in nonhuman foods such as Klason method, spectrophotometric method, acid detergent lignin method, and many more. On the other hand, methods determining DF including RS measure the fraction resistant to the enzymes used in the assay, which mainly includes retrograded amylose. A study was carried out to determine the effect of the activity and purity of enzymes used in various assays of TDF (AOAC Method 985.29) and on specific DF components (RS, fructan, and β-glucan) wherein the measurement of TDF content of RS samples, concentration of α-amylase was found to be critical; however, variations in the level of amyloglucosidase had little effect on TDF measurements. Similarly, contamination with other enzymes led to the underestimation of TDF in various products and was proposed to be discussed further (McCleary 2000). Gas chromatography and HPLC methods were compared for determination of DF (as NSPs) in vegetable products (fresh and processed carrots, sugar beet, and rape). Results obtained using the 2 methods were sufficiently similar and it was concluded that either could be used for determination of fiber as NSPs with equal accuracy (Rodriguez and others 1996).

Conclusions

A wide variety of foodstuffs naturally loaded with SDF are available with their intact potential properties capable of providing significant physiological benefits. High-quality SDF isolated from various sources can be incorporated into a wide variety of commercial beverages, solid foodstuffs like bakery goods, dairy products, and fruit- and vegetable-based products, which all provide potential benefits to the food industry with their consequent increased demand owing to their potent health claims. In comparison to hypo-, hyper-, and normo-cholesterolemic subjects, although the effect of cereal DF on plasma lipids and lipoproteins in the latter is small, these changes would have a significant potential for reducing cardiovascular risk in populations. The palatability and lack of side effects from fiber-rich foods suggest that consumption of more servings of fiber-supplemented foods will also prove acceptable in clinical situations where larger reductions in lipid risk factors for cardiovascular disease are required. Thus, the newer available fiber sources can also be served as a tool to create healthier foods with enhanced bioavailability of nutrients without much change in organoleptic properties. More information on aspects pertaining to their effect on rheological and textural property, however, is needed before upgrading their production to large commercial scale. Thus, with more advanced technological guidelines and analytical methods, their use can be expanded in order to reap physiological benefits in human population.

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