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Review

Dietary fiber as a versatile food component: An industrial perspective

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The continued emphasis on the importance of dietary fibers to the Western diet and the need for products with a lower calorific content is pressuring food companies to allocate more resources to the development of fiber-enriched products. The challenge to the industry is to accomplish this goal without sacrificing the organoleptic appeal of some of their core offerings. As future research details specific nutritional benefits of individual components of dietary fiber, food companies will need flexible alternatives in order to validate new 'functional' food claims and to respond rapidly to emerging trends in fiber-enriched products. These objectives will be achieved by understanding the physicochemical basis for the biotechnical functionality of fibers and by developing, and making available fibers which provide a broad spectrum of bioactive and texture modulating properties.

Keywords: Dietary fiber / Fiber-enriched foods / Hydrocolloids / Plant cell walls / Oligosaccharides / Review

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Abbreviations: CWM, cell wall material; **WBC**, water binding capacity

1 Introduction

The publicity surrounding the burgeoning increase in the number of overweight people in Western society and the heightened consumer interest in good nutrition has refocused the food industry on the merits of including some form of dietary fiber in food products. This seems appropriate, because the increased consumption of meals prepared out of home has in some measure contributed to one incontestable fact: the intake of fiber and fiber-containing foods is well below the recommended levels in all Western countries. While more research is needed to clarify details of the nutritional benefits of dietary fiber, several studies have shown its consumption has been inversely associated with the risk of a number of chronic diseases [1]. The consumer is already aware of the advantages of a diet rich in fruit and vegetables, the major everyday sources of dietary fiber. The food industry can therefore only benefit from including dietary fiber in products with authenticated claims on the short- and long-term gains to be derived from their consumption.

Because dietary fiber remains a nutritional concept it can be accommodated within the ambit of the term 'functional food' or 'nutraceuticals'. In the last 10–15 years functional food has become a popular concept for the food industry. From a marketing point of view functional foods are designed on the basis of some specific health benefit, which is additional to their established role in growth, development, and other normal functions of the body. However, it is important to ensure that emphasizing the nutritional advantages of fiber products does not result in their use only in niche markets. A challenge for the industry is to encourage their widespread and regular consumption in an increasing range of products. To be effective, this must be done without compromising the sensory appeal of the product. The consumer wants variety, good taste but no constraints [2].

Despite the publicity on the health benefits of dietary fiber, many current applications within the food industry have been fuelled as much for technological and economic reasons, as nutritional imperatives. This is particularly true of the hydrocolloids, which have become the basis for a revolution in food fabrication. Their ability to achieve water control enables them to be used to modulate texture in a huge range of products, although more often than not, they are present in insufficient amounts in a single product to constitute a claim in terms of dietary fiber content. Many consist of a single type of polysaccharide and although some are insoluble (*e.g.*, microcrystalline cellulose), most in widespread use are water-soluble. They are clearly not analogous to, nor do they have the consumer appeal of, the natural sources of dietary fiber found in the complex mixture of polysaccharides, which make up the cell walls of fruit, vegetables, and whole-grain cereals.

Plant cell walls consist of a mixture of soluble and insoluble dietary fibers with the latter predominating. While there is some commercial production of such plant cell wall fibers, they have limited application at the present time owing to economic, sensorial and technological constraints. Nevertheless, recent advances in the preparation of such fibers [3] and their physicochemical characterization suggests that tailored fibers from plant cell wall material could be used to enrich food without detracting from the desired texture and flavor. In addition, the rheological properties of whole plant cell walls suggest that they may be used to generate novel textures in a range of applications, which hitherto have not been considered.

A comprehensive review of the applications of hydrocolloids as gelling, thickening, foaming, and emulsifying agents in a bewildering array of food products is beyond the scope of this review and has been detailed elsewhere [4–6]. The present report will focus on some selected developments in the use of the different forms of dietary fiber, which are relevant to the food industry, as well as the research, which underpins their functionality and potential applications.

2 What is dietary fiber and what is it not?

No international consensus has been reached on a definition and yet each year hundreds of new products are launched containing dietary fiber. As consumer awareness of the benefits of functional food grows, so too will pressure for better communication on the nature, components and effects of dietary fiber. The definition proposed by the AACC Dietary Fiber Definition Committee in 2001 is [7]: "Dietary fiber is 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. Dietary fiber includes polysaccharides, oligosaccharides, lignin, and associated plant substances. Dietary fibers promote beneficial physiological effects including laxation, and/or blood cholesterol attenuation, and/or blood glucose attenuation." The regulatory situation in the USA, as well as a number of other countries with regard to labelling of dietary fiber is arbitrary, because it is tied to one or two AOAC methods of determination, as opposed to an accurate definition based on scientific data and common sense. The situation has become more complicated by the fact that some "functional fibers", such as inulin-derived fructooligosaccharides, polydextrose, some polyols, and resistant starch, cannot be determined as dietary fiber by the "gold standard" AOAC methods [8, 9]. They could not therefore, as things stand, be confirmed as dietary fiber for labelling purposes. Recent developments in methods have addressed the situation [10–12].

The definition of what constitutes dietary fiber becomes important to the food industry if a claim is based on a minimum content of dietary fiber in the product. The inclusion of "associated plant substances" in the AACC definition can be interpreted as meaning that dietary fiber embraces such components as tannins and Maillard products and may be extended even further in the future. This is particularly relevant in plant sources, which are either high in phenolic compounds and/or are subjected to a roasting step. Such is the case with cocoa products. Several tons of cocoa shells are produced annually as a by-product of cocoa powder production and are potentially a usable source of dietary fiber. They are rich in tannin-protein complexes and Maillard products. The reported dietary fiber content of cocoa shells could be augmented by 30–40% if Maillard products and tannin-protein complexes were included [13]. This would mean that the level of shells to be added to a product to carry a dietary fiber claim could be significantly lowered.

Whichever definition is used, the consumer has been sold on the fact that dietary fibers are a driving factor in the field of healthy or wellness food. However, it is obvious that in such a complex mixture of ill-defined components (Table 1) not all will have a similar, or even a positive influence on health. Phytic acid and tannins, for example, are known to have negative nutritional properties [14]. Scientists will need to make more sophisticated distinctions between the health benefits of individual components of fiber. This will permit the use of more selective mixtures of

Table 2. 2003 World Food Market Consumption Hydrocolloids[a)]

Hydrocolloid	$ Million	% Total	% AGR[b)]
Starches	792.5	25.4	1.1
Gelatin	775.0	24.9	1.2
Pectin	312.7	10.0	5.7
Carragenan	305.4	9.8	2.9
Xanthan	238.6	7.7	5.2
Agar	146.3	4.7	2.4
Locust bean gum	128.6	4.1	2.1
Gum Arabic	109.8	3.5	2.4
Alginates	87.5	2.8	2.5
Carboxymethylcellulose	67.3	2.2	2.7
Guar gum	53.8	1.7	2.6
Microcrystallinecellulose	46.8	1.5	2.1
Methyl cellulose/HPMC	33.4	1.1	6.2
Other	19.3	0.6	2.8
Total	3117.0	100	
Total excluding starch/gelatin	1549.5	49.7	

HPMC: hydroxypropylmethylcellulose
a) Food Hydrocolloids Conference March 21–23, 2004, San Diego; data provided by IMR International and presented by D. Seisun
b) Annual growth rate

dietary fibers, which target a specific health need with greater scientific credibility than at present.

3 Fiber-enriched foods: a crucial role for industry

For a healthy diet the recommended daily dose of dietary fiber is between 25–30 g per day [15]. At the beginning of the 90s it was reported that 10–25% of Americans ate no vegetables, and 47% not a single serving of fruit, on a given day [16]. Without doubt, palatability, convenience, and price were tending to overwhelm healthy eating decisions. This in spite of the fact that consumers placed nutrition second in importance to taste in factors for food selection [17]. However, more recent surveys indicate that public awareness of the benefits of consuming dietary fiber is growing [18]. According to a 2001 Healthfocus International Trends report, more than 40% of American and Australian shoppers and 33% of Western European shoppers said that "high fiber" was an extremely important label claim [18]. The relevant news for food manufacturers was that consumers put dietary fiber content third (behind how to limit fat and calories) as the most sought after topic for health information in supermarkets.

Aside from the economic imperatives, the industry has an obligation to improve the nutritional benefits of its products, because, whether we like it or not, in the Western world pre-prepared foods are gaining an increasing share of the food market at the expense of meals prepared in the home. Fuelled by significant progress in technologies, the industry can now provide a diverse range of prepared foods, with increasing consumer appeal. Dietary fiber could be included in many of these recipes providing they were compatible with these technologies and did not compromise the sensory quality of the product. If all dietary fiber came from cereal brans this would not be possible, as such fibers have a limited functionality in terms of water control and would result in some negative sensory attributes in the product. Fortunately, there are now sources of dietary fiber which possess a much broader spectrum of technological functionality. From an industrial perspective they can be separated into three broad classes: (i) hydrocolloids, mostly soluble polysaccharides; (ii) bioactive oligosaccharides; (iii) whole plant cell wall materials derived from cereal grains, fruits, and vegetables. All possess both physiological and technological functionalities to varying degrees, which dictate their respective applications.

4 Hydrocolloids

Hydrocolloids are those substances, which influence the physical properties of water. In particular, hydrocolloids swell and produce a viscous solution or dispersion when exposed to water. They include functional proteins, such as gelatin, myosin, albumens, and globulins, but the largest range is polysaccharide-based, including such polymers as galactomannans, glucomannans, pectinaceous materials, arabinogalactans, seaweed-based extracts, the microbials (gellan and xanthan), and other macromolecular entities, such as cellulosics, glucans, and starches [4]. In all, there are approximately 150 different hydrocolloids in use today but those listed in Table 2 dominate the food industry. In 2003, the value of the world market for these hydrocolloids was $ 3.1 billion (personal communication D. Seisun) but only half of this could be attributed to hydrocolloids classified as dietary fiber. Gelatin and starch, two hydrocolloids which for the most part are not dietary fibers, contributed the remainder. The annual rate of growth in the world market was strongest for pectin, xanthan gum, and cellulose derivatives. Starch and gelatin had the slowest rate of growth, suggesting that alternative hydrocolloids are being used in an increasing number of applications.

The food industry is constantly looking for economic ways of generating products with even more desirable textural and organoleptic properties than are currently provided by available hydrocolloids. Thus, despite the diversity of hydrocolloid functionalities at hand, there is an onus on researchers to investigate new sources of hydrocolloids with more specific functionalities, or to use existing hydrocolloids in innovative ways to improve and optimize the tex-

Table 1. Constituents of dietary fiber

Polysaccharides and resistant oligosaccharides
Cellulose
Hemicellulose
Pectin
Gums
Mucilages
Resistant starch
Fructans, oligofructans
Galactooligosaccharides
Analogous carbohydrates
Dextrins (oligosaccharides produced by acid hydrolysis of starch)
Synthetic derivatives (methylcellulose, hydroxypropylmethylcellulose)
Lignin
Associated plant substances
Waxes
Phytate
Cutin
Saponins
Suberin
Tannins

Report of Dietary fiber definition committee September 2001 [7]

tural and organoleptic properties of products. The first approach has the disadvantage that a large financial investment is required to legitimize a new hydrocolloid and for this reason it is unlikely that we will see any truly new types of hydrocolloid in the foreseeable future. It is the second approach that offers more likely opportunities for industrial development and this aspect will be discussed in the present review.

4.1 Hydrocolloid-protein interactions in food formulations

One way of extending the application of dietary fibers, and perhaps of mitigating some of the unwanted side-effects which can arise when products are enriched with too much pure fiber, is to incorporate fiber into food as mixtures with other macromolecules. This is in fact what nature does, as most foods contain proteins and polysaccharides and it is the interaction and spatial arrangement of these macromolecules, which confers a specific structure and texture on food material. It is therefore not surprising that one area of increasing interest in food science is that of the phase separation phenomena which accompany mixtures of proteins and polysaccharides [19]. Many model systems have been studied in order to understand and control these interactions with a view to designing products with novel structural properties. Protein-polysaccharide mixtures often show better and more versatile functional properties than the individual components alone [20]. As a consequence, the novel hydration, structure forming, and surface properties of the mixtures lend themselves to applications in food formulations as fat replacers, texturizers, and stabilizers of dispersed systems. Additionally, as long as the bipolymeric mixtures consist of validated food ingredients, innovative developments in food fabrication can be made without the need for legislative approval.

Phase separation involves two kinds of behavior: complex coacervation and thermodynamic incompatability. Complex coacervation promotes coprecipitation of protein and polysaccharide under the influence of net attractive interactions between protein and polysaccharides [21, 22]. Thermodynamic incompatibility, on the other hand, involves separation of protein and polysaccharide-rich phases under the influence of repulsive interactions, mainly excluded volume effects [23]. A biopolymer system consisting of an anionic polysaccharide and a globular protein can show either behavior or both, depending on the pH value of the system. For example, when a protein such as β-lactoglobulin is combined with various nongelling anionic polysaccharides the systems can show thermodynamic incompatibility (pH > p*I* of the protein) or complex coacervation (pH < p*I* of the protein). Figure 1 demonstrates this change with the xanthan/β-lactoglobulin biopolymer system. At pH 7.0 both the protein and xanthan have negative charges and show phase separation based on incompatibility. At pH 4.0 the protein carries a net positive charge and there is an electrostatic attraction between the protein and the negatively charged xanthan. The result is that protein covered xanthan fibers are formed at pH 4.0 but not at pH 7.0. Thus, it is possible to direct the microstructural design in this mixed biopolymer system merely by changing the pH.

Coacervate systems are used in milk products where low amounts of carrageenan are added to stabilize and prevent whey separation in a number of dairy products [24]. The negatively charged carrageenan interacts with the micellar caseins to form a stabilizing network, preventing protein-protein interaction and aggregation during storage. Patents have been filed for shelf-stable acidic food dressings, which consist of xanthan gum-soybean protein complexes [25] and for protein-polysaccharide complexes for the interfacial stabilization of systems with two or more phases, such as foams and emulsions [26]. The latter has potential applications for ice-cream, chocolate, dairy products, and coffee creamers. The increasing number of patents filed in this area by food company-based research groups demonstrates the interest and potential usefulness of phase separation in food applications [20].

An area of particular relevance to the food industry is the effect of shear on biphasic systems. When biopolymer mixtures are subjected to processing the property of flow is superimposed on the phase separation and this can affect

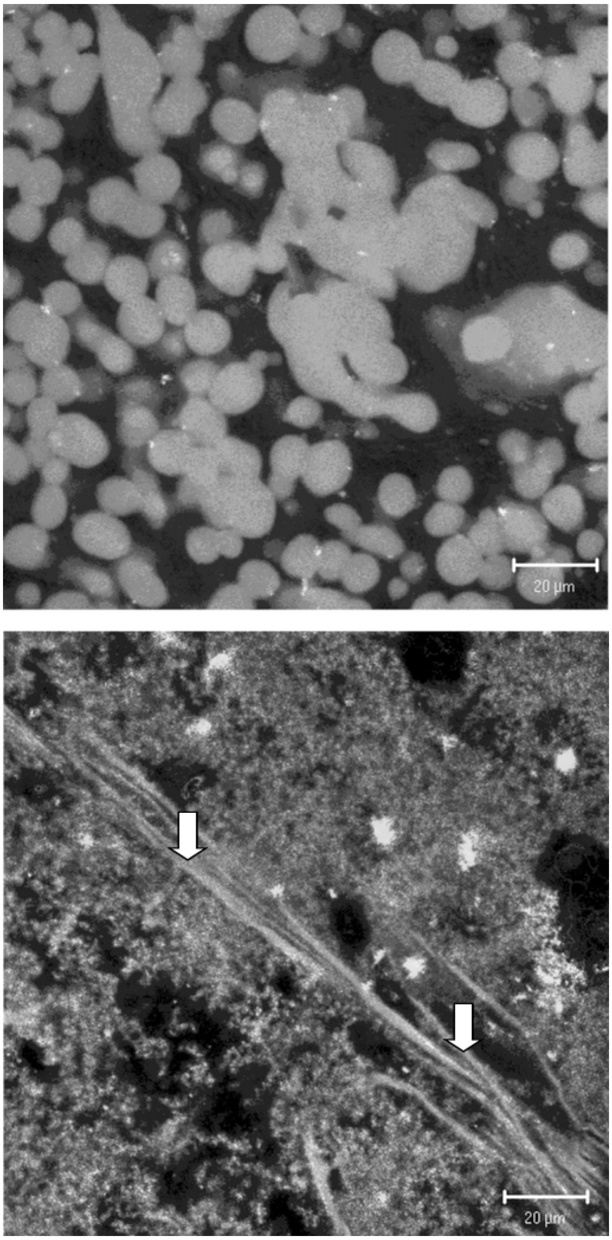

Figure 1. Confocal laser scanning microscopy (CSLM) of mixture of β-lactoglobulin 7 wt.-% and xanthan gum. 0.8 wt.-% heated for 20 min at 80°C in the presence of 10^{-8} M rhodamine at ph 7.0 (upper) and pH 4.2 (lower) (reproduced with permission from S. Schmitt and E. Kolodziejczyk, Nestlé Research Centre).

the final microstructure and textures produced [27, 28]. The advantage is that physical treatments of biphasic systems can generate additional structures with novel properties. By applying shear to a biphasic system before gelation it is possible to trap a dispersed phase in an anisotropic structure [29, 30]. Antonov and co-workers [31] demonstrated that deformed particles generated by shear could be trapped during gelation, forming capillary like structures filled with fibers. These can be used for textured protein products. It is also possible to prepare an emulsion or dispersion in a biopolymeric system with controlled shape of the dispersed phase so that the composition can be carefully controlled [32]. This could have applications in products, such as creams, margarine, mayonnaise, dressings, sauces, and other food emulsions.

The sensitivity of biphasic systems to alteration following physical treatment does have a downside. Most manufacturing includes some stage of physical perturbation and even very slight shear forces can influence the morphology of the mixture, which in turn can induce unwanted changes to rheology, and sensorial properties of the system. Temperature is another parameter that is particularly relevant to protein-polysaccharide interactions. If the temperature of a processing step is high enough to denature the protein then protein-protein interactions can predominate over the targeted protein-polysaccharide interactions in the system.

The commercial application of phase separation principles involving polysaccharide-protein systems has not kept pace with the outpouring of publications and patent applications in the field. This is largely due to the fact that we are still some way from being able to design, and control the microstructure of mixed biopolymer composites so that targeted rheological and sensorial properties of products can be consistently guaranteed. In a recent review, it was stated that most of the important parameters affecting protein-polysaccharide interactions were well documented but the current need is for a greater focus on mechanisms underlying the structure building kinetics, and thermodynamics of biopolymer mixtures [33]. Understanding the driving forces for phase separation will shed light on questions of how the phase structures form initially and then evolve. Armed with this knowledge, the use of protein-polysaccharide complexes in processed food products promises not only another avenue to promote the consumption of dietary fiber but to do it in a way which mimics nature herself.

4.2 Enzymatic transformation of hydrocolloids

Attempts to improve and diversify hydrocolloid functionality by enzymatic modification of polysaccharides falls into three categories: depolymerizing, debranching, and synthetic. Of these, depolymerization by endo-glycosyl hydrolases is the most common, followed by debranching by exoglycosidases. An example of the latter two approaches is provided by the enzymatic hydrolysis of galactomannans using galactomannan-degrading enzymes. This has produced a range of novel galactomannans and galacto-manno-oligosaccharides from guar. Debranching of guar gum with α-galactosidase increases the degree of self-association of the galactomannan and the capacity to undergo gel formation with other polysaccharides, such as xanthan gum [34]. On the other hand, the high viscosity of guar gum in solution limits its use at physiologically effective concentrations in liquid preparations. A process for producing partially hydrolyzed guar gum (PHGG) with a lower viscosity than the native guar gum has been described [35]. Assuming that the metabolic and nutritional properties of the PHGG correspond to those of guar gum it can be used at higher concentrations for the fiber enrichment of food products. The PHGG has been marketed under the name of SUNFIBER[R] (Taiyo Kagaku Co., Ltd, Japan) and has been promoted on the basis of both its technological and physiological properties.

The idea of creating and controlling a hybrid structure from a pool of monosaccharide residues by using a synthetic enzyme remains in the realm of the *in vivo* biosynthetic process. Many glycosyltransferases of the Leloir pathway require expensive sugar nucleotides as glycosyl donors and non-Leloir pathway enzymes need sugar-1-phosphates as glycosyl donors which are also costly [36]. The most successful *in vitro* experiments have been done with glycosidases by either reverse hydrolysis or by transglycosylation [37]. This group of enzymes uses the relatively inexpensive mono- or disaccharides as glycosyl donors. They have been used commercially to generate nutraceutically and technologically valuable oligosaccharides, which would be difficult to produce by chemical synthesis.

Two groups of prebiotic oligosaccharides which are now produced by reverse hydrolysis using glycosidases are the fructo- and galacto-oligosaccharides. The fructo-oligosaccharides are produced from sucrose using a fungal fructosyltransferase (ACTILIGHT[R]; Béghin Meiji Industries, France). The sucrose plays the role of fructose donor and fructose acceptor [38]. The reaction is controlled to optimize the desired ratio of oligosaccharides of a defined DP [39]. The galacto-oligosaccharides are produced by treating lactose with β-galactosidase which has transglycosylation activity [40]. These oligosaccharides are sold commercially in Europe as Elix'or[R] (Borculo Domo Ingredients, The Netherlands).

So far the two most important glycosyl transferases that have biotechnical potential are cyclodextrin glucanotransferase and dextransucrase [41]. The first is able to convert starch to a mixture of cyclic malto-oligosaccharides (cyclodextrins) which not only possess prebiotic properties but can be used as carriers and stabilizers of color, flavor, and vitamins in products [42]. Dextransucrase is able to synthesize dextran using sucrose as glycosyl donor. The enzyme is able to form novel oligosaccharides using different sugars as acceptors. Using the dextransucrase from *Leuconostoc mesenteroides* and 1-*O*-α-D-glucopyranoside as an acceptor, a series of glucooligosaccharides containing α-(1–2) linkages were produced [41]. These are in demand for their prebiotic properties and are now produced on an industrial scale.

Although it has been shown that polysaccharides structure can also be modified by synthetic enzymes [43–45] their commercial exploitation to improve the functionality of existing hydrocolloids is not yet a reality. The promise lies in advances in enzyme technology where genetically modified hosts may be able to produce synthetic enzymes which can alter hydrocolloid structure in a functionally useful way. Enzymes are the perfect tools for this purpose, because if the enzyme is pure, the modification is predictable, selective, and occurs without inadvertent alterations to the remainder of polysaccharide structure. The major problem with the approach is that the structure/functionality relationships of many hydrocolloids are not defined enough for scientists to be able to predict with certainty the effect of a structural alteration on the physicochemical properties of the resultant polymer. Despite the promise of genetically tailored enzymes, biotech companies will be reluctant to invest time and money to generate novel enzyme activities which successfully mediate a specified structural change, without being certain that the modified hydrocolloid will deliver the targeted functionality.

4.3 Arabinogalactan: a neglected dietary fiber?

Arabinogalactans (AGs) and arabinogalactan-proteins (AGPs) are consumed daily in a range of fruit, vegetables, cereals, and wine [46]. They have unusual physicochemical properties and are isolated and exploited commercially from two natural sources, Acacia plants and Western Larch trees [47]. Nevertheless, in the 2001 edition of the *Handbook of Hydrocolloids* [4], although there were chapters devoted to 25 different types of hydrocolloids, AGs and AGPs, with one exception, were not among them. However, there is increasing awareness of the fact that AGs and AGPs possess important bioactive properties and that, as a consequence, the commercial profile of this important category of hydrocolloids may be about to rise.

The exception for industrial use is gum arabic or acacia gum which has been an important hydrocolloid since ancient times but its application to date has been largely technological. It is a mixture of glycoproteins, AG and AGP, and is obtained as a tree gum exudate [48]. The highly branched nature of the structure of gum arabic, and AGs in general, means that in solution the molecule adopts a relatively small hydrodynamic volume and as a consequence gum solutions become viscous only at high concentrations [4]. Many of its applications are based on the fact that it can be used at sufficiently high concentrations to allow the protein-rich component of gum arabic to be an effective emulsifier, as it is able to adsorb preferentially on to the surface of oil droplets. Several reports have also been made of its prebiotic and cholesterol-lowering properties [49, 50].

Another AG of commercial use is isolated from the Western Larch (*Larix occidentalis*). As well as its technological applications, Larch AG is becoming important for its bioactive properties [51, 52]. It possesses prebiotic properties, being fermented in the distal gut microflora resulting in elevated levels of short-chain fatty acids, primarily butyrate and propionate. As important as its role in digestive health, Larch AG has also been receiving attention for its ability to enhance immune system performance [53] and is now marketed as an "ImmuneEnhancer ™ AG" (Larex Inc.). It appears to function in this role by blocking bacteria and viruses from attaching to cell membranes on the liver and other organs preventing infections from becoming established. Tumor metastasis to the liver has been shown to be impaired by Larch AG [54–56].

The immune-enhancing properties of AGPs are also believed to be the active ingredient in Echinacea [57] and *Lycium barbarum* or wolfberry, although in the latter, other components have also been implicated [58]. Wolfberry has been a source of a traditional Chinese herbal medicine that has been used for over 2000 years as an anti-aging health food [59]. The AGP was purified from wolfberry as the glycoconjugate (LbGp4) and demonstrated high immunoactivity. In contrast to most AGPs it has been shown that the AGP from wolfberry is a type 1 AG containing a backbone of β-1,4 linked galactosyl residues [60]. LbGp4 and its glycan, promoted splenocyte proliferation in normal mice, and the effects of the glycan chain were stronger than those of glycoconjugates, indicating that the immuno-modulating activity resided in the AG chains. In a clinical trial on 75 cancer patients, orally administered *Lycium barbarum* polysaccharide (LBP) was used in combination with lymphokine activated killer (LAK) and interleukin-2 [61]. The treatment led to a significant higher regression of cancer than without the presence of LBP, and an increase in LAK cell activity was observed. In another study, it was reported that LBP stimulated the T cells to produce interleukin-2 in the elderly [62].

The latest source of an AGP to be suggested as having some commercial potential is that contained in the green coffee bean. Coffee bean AG was only recently shown to be an AGP [63]. The isolated proteoglycan has a very high molecular weight average (6000 kDa) but possesses characteristics in common with gum arabic in terms of its surface-active properties (Redgwell *et al.*, 2004, submitted for publication). Nothing is known about the prebiotic or immune-enhancing properties of coffee AGP. Considering the almost universal consumption of coffee beverages and the fact that AGPs are solubilized to some extent in all coffee drinks, it would seem to be in the industry's interest that the bioactivity of these hydrocolloids should be investigated. On a broader front, the unusual solution properties of AGs and AGPs and their reported role in digestive health and immune-modulation, suggests that they could be conveniently incorporated into a wide range of products, at concentrations which would allow a persuasive functional food claim to be made.

4.4 Chemical additives or dietary fiber?

Despite the value of many hydrocolloids in food fabrication, it is likely that the consumer does not see them in the same positive light as fibers from more natural sources, such as whole grains or fruits and vegetables. When used in food products, it is mandatory that hydrocolloids, such as gellan gum, xanthan gum, galactomannans, alginates, the cellulose-derived gums, *etc.*, are labeled by an E-number, denoting a chemical additive and this can be perceived by the public as a negative factor. Their presence in fiber-fortified food is therefore not altogether consistent with the healthy, natural image which food companies wish to promote by publicizing the presence of dietary fiber in their products. In part this is due to the fact that the consumer may see soluble hydrocolloids as industrially expedient texturizers, rather than as dietary fibers with health benefits. This is unfortunate, because alginates, pectic polymers, galactomannans, and carrageenans are obtained from natural sources which are themselves consumed as whole plants in many parts of the world. These hydrocolloids are dietary fibers, which possess physiological functionalities which in some cases are equivalent to those from whole grain-, fruit-, and vegetable-derived plant cell walls. The manufacturer is unable to highlight this feature in products which contain hydrocolloids, because most are used below the threshold concentration at which a health claim is permitted. Nevertheless, with the rise in the use of soluble hydrocolloids in prepared foods and the increasing consumption of the latter, the cumulative content of the hydrocolloids in several products could make a significant contribution to the daily dietary fiber intake. To take advantage of this fact, the physiological functionality and potential health benefits of hydrocolloids as dietary fibers needs more emphatic validation. This will enable the food industry to convey to the consumer a much stronger message on the positive attributes of these industrially important food components.

5 Bioactive oligosaccharides: the prebiotic effect

A prebiotic is a food ingredient that it not hydrolyzed by human digestive enzymes in the upper gastrointestinal tract and beneficially affects the host by selectively stimulating the growth and/or activity of one or a limited number of bacteria (*Bifidobacteria* or *Lactobacilli*) in the colon that can improve host health [64]. A convincing demonstration of a specific health affect *in vitro* and *in vivo* for human subjects was for inulin and inulin-type fructans. These compounds lead to an increase in barrier function and reduction in risk of intestinal infections [65, 66]. Other nondigestible oligosaccharides (NDOs) with reported prebiotic activity include galacto-, isomalto-, soybean-, xylo-, and gentio-oligosaccharides, lactulose, and lactosucrose. Evidence for health effects of the most important NDOs along with applications in the food industry has been reviewed recently [67].

The prebiotic properties of NDOs appear superior to those of many polysaccharides which are frequently fermented by colonic bacteria but not selectively by probiotics [68]. Nevertheless, the structure-function relationships of prebiotic oligosaccharides are in need of investigation, particularly on the relationship between molecular weight, monosaccharide composition, glycosidic linkage, stereochemistry and prebiotic activity. Armed with this knowledge, predictive rules could be applied to NDOs, which will enable more rational, and compelling ingredient development.

The rheological properties of most NDOs mean that they are more versatile in the range of food types to which they can be added than are the polymers from which they were derived. This is because NDOs do not show gelling or viscosifying properties to the same extent and therefore do not modify the texture of a product in the same way as xanthan gum and pectins, *etc.* They can also be purified more easily and do not contain as many associated substances. Thus, they can confer a health benefit to a variety of end products, such as dairy, breads, cereals, snacks, beverages, chocolates, meat, and confectionary, without significantly compromising organoleptic appeal. In Europe the prebiotic market is still in its infancy, the $ 87 million fructan segment being the most developed. Of this 62% is in dairy, 20% bakery, 5% processed meats with the remainder spread among other applications [69]. They obviously offer the food industry an opportunity to markedly expand sales in many sectors of the functional food sector. To aid this process both manufacturers of NDOs and the food industry need to raise the level of public awareness of prebiotics and their potential benefits, to that of dietary fiber.

Finally, the surface has only been scratched in terms of exploiting the potential range of available NDOs. Industrial processes produce tonnes of polysaccharide-based waste, which could be used for the generation of NDOs [70, 71]. In the future the use of enzymatic and/or acid hydrolysis on naturally occurring polysaccharides could allow the generation of NDOs with a range of chemical complexity beyond anything currently available. This complexity will allow them to survive the adverse conditions of the gastrointestinal tract and to be fermented at a slower rate, providing a prebiotic benefit at the distal end of the colon, a common site for cancer initiation [68].

6 Plant cell wall materials

An integral part of a healthy lifestyle is the consumption of fresh, natural food and this is often associated with images of fruit and vegetables and whole-grain cereals. Although the health benefits of these foods can be attributed to many different nutrients, the dietary fiber content has become a key component in promoting the belief that diets based on a significant intake of fresh fruit and vegetables has long-term health benefits.

The dietary fibers in these foods are derived almost entirely from the plant cell walls, the major structural components of fruit and vegetables [72, 73]. Unlike the soluble hydrocolloids, the plant cell walls consist of a mixture of several different types of polysaccharides, proteins, lignin, and associated substances [74]. The complex chemistry of this structure of 'soluble' and 'insoluble' polysaccharides and other macromolecules has only been partially characterized. Their technological and physiological functionality, although generally accepted, awaits further clarification in terms of the individual contribution of each type of macromolecule present in the cell wall. From an industrial standpoint this is not a major setback, and may in fact be an advantage, as the consumer already accepts that dietary fibers in their entirety are beneficial for a healthy diet.

6.1 Dietary fiber from parenchymatous tissue of fruit and vegetables

Despite their positive image, the use of dietary fibers purified from whole plant cell walls in manufactured food products is low compared to the soluble hydrocolloids. This is because such materials have until now had some limitations in terms of their supply and technological functionality. Nevertheless, things are changing with regard to the availability of a range of dietary fibers, which are now being produced and promoted as innovative, healthy and multifunctional.

Fibres produced under the 'Vitacel' brand (J. Rettenmaier & Söhne) include wheat, oat, tomato, apple, and orange fibers. The manufacturers report that the fibers have a good water binding capacity (WBC) and special sensory properties due to the technology used and the very fine milling (particle size ∼30 μm). The fibers do not negatively affect the taste of the enriched product when compared to dietary fiber from cereal-derived brans or beets, which can confer a particular flavor and color and can lead to consumer rejection. The 'Vitacel' fibers can be used to enrich a wide spectrum of products including breads, cookies and crackers, pasta, muesli bars, cooked sausage, *etc.* While these fibers are a useful addition to the dietary fiber range they do not approach the potential WBC of the parenchymatous cell walls from which they were derived. With further improvements in processing technologies, fibers could be isolated from the parenchymatous tissue of fruit and vegetables which possess markedly enhanced WBCs.

6.1.1 Cell wall materials with improved functionality

For the most part parenchymatous tissues of fruits and vegetables are nonlignified and extremely hydrophilic. They therefore have a natural affinity for water, which makes them ideal candidates as viscosifiers and thickening agents. The ability of fruit cell wall material (CWM) to interact with water is enhanced in some fruit by the ripening process. In several fruit which ripen to a soft texture (tomato and kiwifruit) the isolated cell walls have an increased capacity to swell and viscosify in aqueous suspensions compared to cell walls from unripe fruit [75]. This has been attributed to structural changes to the cell wall polymers mediated by cell wall-degrading enzymes, which are activated by the ripening process. If this enhanced WBC is to be maintained and exploited, methods of isolation of the CWM must be carefully controlled.

It has been shown that the technological functionality of apple CWM is considerably modified during isolation, or in general processing [3, 76–80]. If the CWM is dried from an aqueous suspension the cell walls shrink and collapse and the physicochemical properties of the fiber bear no resemblance to the cell wall *in vivo*. If the CWM is washed with an organic solvent, such as 94% alcohol, before drying, damage to the cell wall structure is minimized and the ability to entrap and bind water is greatly enhanced. By controlling the isolation conditions in this way CWM from apple with a WBC as high as 70–80 g water/g CWM has been prepared [81].

Another factor in maximizing the particular technological functionality of fiber is the source and purity of the tissue from which the CWM is isolated. At this point we should discriminate between CWM and dietary fiber. The former can be viewed as a more pure form of the latter, particularly when it is isolated from one type of tissue like the pericarp of an apple or tomato. Dietary fiber on the other hand is often a heterogeneous mixture of tissues. In some instances it is the residual by-product of the isolation of a more valuable component. Tomato fiber, for example, may be a residual by-product of lycopene extraction and is therefore a heterogeneous mixture of several tissue parts. These can include hydrophobic tissues like the skin or tissue-dense material like seeds with a decreased affinity for water. While this may not be a disadvantage in terms of the physiological benefits of the fiber (in fact the opposite may be true), it can be a serious disadvantage if the object is to obtain a fiber, which maximizes a specific technological functionality (*e.g.*, WBC).

A highly purified CWM known as Herbacel AQ plus citrus fiber, has a dietary fiber content of 92% and a WBC of 17–25 g/g fiber (Herbafood Ingredients). The fiber is readily dispersible in cold water to give smooth viscous suspensions at concentrations of 2% or more. It has been reported as an improved fruit fiber with advantages for processing applications [82–84] and has been used to produce low calorie/fat products or to improve the structure of high water containing products, such as sausages or ice cream. Typical application fields include: (i) low-fat sponge cakes; (ii) sugar-reduced muffins; (iii) low-fat curd cheese preparation; (iv) whipped curd cheese (improved and stable overrun at higher temperatures); (v) mayonnaise, dips, and dressings (viscosity, structure in low-starch products); (vi) drinks (to enhance viscosity, pulpy texture); (vii) frankfurter sausages (texture, syneresis in low-meat formulations); (viii) fillings/sauces (to avoid gummy-like texture); (ix) instant drinks (enhance satiety due to high swelling).

The citrus fiber can be added to ice cream or sorbets at levels of 1.5–3%, which is physiologically significant. It acts as a stabilizer, preventing proteins from coagulation and reducing problems of syneresis. It also enhances melting stability of the final product during transport and because of its texture-forming properties does not reduce creaminess or mouth feel [83].

An interesting property of some fruit derived CWMs is that a high shear treatment of an aqueous suspension causes it to be transformed from a normal suspension of swollen particles, to a colloidal suspension, which at concentrations of 1% or more becomes a thick gel (Fig. 2). This property has been reported for kiwifruit cell wall material [85]. The exact mechanism of this phenomenon is not known but it seems that following high shear the cell wall particles are dispersed in such a way that their WBC increases dramatically either by the formation of a three-dimensional network or by increasing the number of particles which possess double-electrical layers which are known to surround cell wall particles of parenchymatous tissue [86]. The formation of a smooth gel from what is essentially insoluble cell wall particles, demonstrates the potential versatility of these fruit-derived CWMs for providing a range of textures for food products.

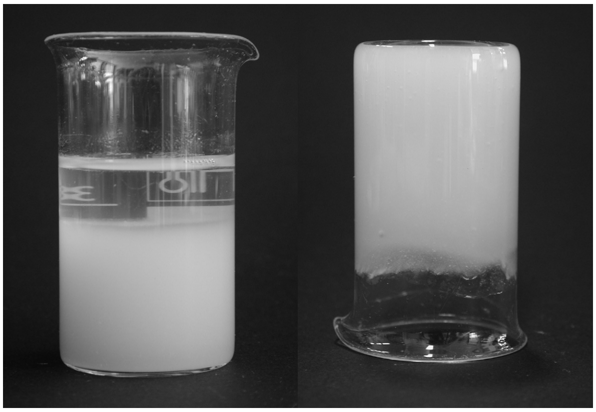

Figure 2. A 2% aqueous suspension of cell wall material from the parenchymatous tissue of ripe fruit. Left: before shear. Right: after shear.

6.2 Whole-grain cereals

6.2.1 Health claims

Dietary fiber contained in whole-grain foods has a higher consumer profile than fibers from other sources. Americans find the health benefits of whole grains particularly believable: 81% are of the opinion that foods made with whole-grain oats can help reduce cholesterol [18]. Although previously there was some debate about the effectiveness of oat bran β-glucan in lowering blood cholesterol, further studies have shown that the consumption of cereal fiber was strongly associated with a reduced risk of total myocardial infarction [87] and this has lead to the recent whole-grain foods health claim approved by the U.S. Food and Drug Administration [88]. More recently, several articles have been published which have reinforced the case of whole grains as health promoting components of the diet [89 – 93]. The implications of this for the food industry are obvious but the health claim begged an important question – What is a whole grain? In 1999 the AACC Board of Directors approved and accepted a definition of whole cereal grains which stated: "Whole grains shall consist of the intact, ground, cracked or flaked caryopsis, whose principal anatomical components – the starchy endosperm, germ and bran – are present in the relative proportions as they exist in the intact caryopsis" (www.AACCnet.org).

This definition was designed for industry and regulatory agencies and includes words that would not be understood by consumers nor help them to select whole-grain foods. A revised consumer-friendly definition has recently been proposed by the AACC Grains Health Task Force but has yet to be approved: "Whole cereal grains and foods made from them consist of the entire grain seed usually referred to as the kernel. The kernel is made of three components – the bran, the germ, and the endosperm. If the kernel has been cracked, crushed, or flaked, then in order to be called whole grain, it must retain nearly the same relative proportions of bran, germ and endosperm as the original grain" (www.AACCnet.org).

In Europe the UK Joint Health Claims Initiative published an endorsement that whole grain foods are associated with a healthy heart [94]. However, the current UK and EU food-labelling legislation prohibits claims which attribute to a foodstuff the property of preventing, treating, or curing a human disease. Thus, reduction of risk of disease claims is not permitted at present.

The establishment of the USA health claim is an important step for food companies that wish to promote whole-grain products as functional food. The dissemination of the whole grain health message is necessary to heighten consumer awareness and knowledge of the importance of whole grains. Current strategies to increase whole-grain consumption are probably best aimed at the important breakfast meal, because until now whole-grain use has been mostly in breads and cereals [95]. Medium term planning, however, should also include attempts to diversify the range of products with whole-grain components beyond that of the breakfast meal. The problem is that there are undoubtedly some negative affects on the textural and organoleptic properties of products made with dietary fiber from whole-grain cereals. This is due to a set of physiochemical properties, which are quite different, to those of the fibers from the parenchymatous tissue of fruit.

6.2.2 Whole-grain cereal fiber *versus* parenchymatous plant cell wall fiber

The major nonstarchy polysaccharide components of the primary cell wall of fruit and vegetables differ markedly from those in cereals [72]. Both contain cellulose but the latter are dominated by mixed linkage glucans and arabinoxylans, while the parenchymatous tissues of fruit consist predominantly of pectin and xyloglucan. This may be an important difference in terms of physiological functionality but until more is known on the polysaccharide specific effects of dietary fiber, its significance cannot be assessed. In addition, the CWM of fruit is mostly a mixture of hydrophilic polysaccharides, which has the ability to interact and bind water in such a way that it can form colloidal dispersions or gels and render very smooth and fine textures to products. Providing the cell walls are washed effectively most of the associated secondary metabolites, such as flavonoids, phenolics, and lipids, which affect the flavor profile of the fiber, can be eliminated. What remains is basically a 'pure' polysaccharide matrix with a neutral flavor impact.

The whole-grain-based fibers on the other hand have a more heterogeneous composition. A diverse range of chemical components are held in a highly insoluble matrix which contains the highly cross-linked compound lignin as well as range of phytochemicals, which includes lignans, tocotrienols, phenolic compounds, phytosterols, vitamins, and antinutrients, such as phytic acids, tannins, enzyme inhibitors, protein, and lipids [93]. These are not easily removed by chemical extraction and have a marked impact on the sensory profile of any product to which whole grain fiber is added. Overall the physicochemical properties are more hydrophobic than the fruit cell wall material and the dietary fiber is more difficult to disperse in an aqueous environment, which raises problems of a textural nature.

Purely on the basis of its dietary fiber content, CWM from parenchymatous tissue also has an advantage. CWMs can contain between 60–90% dietary fiber, whereas the bran fraction of some whole-grain cereals, such as oats, wheat, and rice, contain between 16–32%, 35–45%, and 20–33% total dietary fiber, respectively [96, 97]. This is of course offset by the fact that the yield of CWM from fruit and vegetables on a fresh weight basis is very low (1–4%). It may be possible for researchers to devise technologies which remove some, or all of the offending components from the whole-grain source so that the dietary fiber is sensorially less problematic. However, it must be remembered that the health claim made for whole grain cereals is not solely based on its fiber content, a fact emphasised by an additional press release from the AACC Grains Health Task Force: "The benefit of keeping the whole grain components in proportion is that it provides a balance of nutrients and non-nutrients (such as phytochemicals) that may work together to reduce the risk of chronic disease" (www.AACCnet.org).

Thus, whole grain cereals contain important associated compounds including phytosterols and folates which have been reported to have several beneficial effects including the prevention of defects in the developing foetus and decreasing serum homocysteine, regarded as risk factor for cardiovascular diseases [98]. Currently, there is no clear picture on the cause and effect relationship between a component of dietary fiber or compound associated with dietary fiber, and perceived health benefits. Some, or even all of the proposed benefits may result from the small amount of associated plant substances, which are present in many dietary fiber preparations currently in use. This may certainly be the case for the more chemically complex whole cereal grain fibers and for this reason it would seem a wise option for the food industry to continue to search for and develop technologies which allow the incorporation of chemically unmodified whole grain-based fiber into an increasing range of popular product categories.

7 Dietary fiber and satiety

One approach of increasing interest to the food industry for the prevention of weight gain is to provide products with high satiating capacities and low-energy densities. Dietary fibers would seem ideal candidates to fulfill this role. Under conditions of fixed energy intake several studies have indicated that an increase in either soluble or insoluble fiber consumption increases post-meal satiety and decreases subsequent hunger but there is no indication of which is the more effective [1, 99, 100]. Studies have demonstrated that high fiber affected the body fat levels more than low-fat diets [101] and that before weight reduction a decrease in total fat mass was observed [102].

Although there are several proposed reasons for the effectiveness of fiber in this role [103], little is known about the exact mechanism of the regulation of meal initiation or meal termination [104, 105]. At least 31 different hormones or peptides have been implicated in food control intake and several of the latter in the gut have been linked to food regulation [106]. Cholecystokinin is released from the small intestine and has been reported to delay gastric emptying, blunt glycemic responses, and enhance satiety [107]. A glucagon-like peptide has been reported to do the same thing [108]. More recently, the plasma levels of the stomach peptide ghrelin [109] were reported to rise before each meal and to drop immediately after each meal [110]. These peptides, therefore, offer an apparent way to conduct scientifically based clinical studies to monitor the satiety index of foods. However, some doubt exists as to their reliability as indicators of satiety. Satiety scores have increased in studies with soluble fibers but this was not always accompanied by an increase in plasma cholecystokinin [111].

The effect of both soluble and insoluble fiber on the properties of pasta and their satiety inducing capacity have been reported. The consumption of pasta containing β-glucan prolonged elevated cholecystokinin levels [112]. The nutritional and physicochemical characteristics of dietary fiber-enriched pasta showed that both the type and amount of added fiber influenced the overall quality of both raw and cooked pasta [113]. Overall pasta elasticity was reduced with fiber addition and this was related to the disruption of the protein-starch binding during pasta matrix formation. This results in a loss of material during cooking. Conversely, the inclusion of soluble fiber, such as guar gum, resulted in the entrapment of starch granules within a viscous protein-fiber starch network and a reduction in the loss of glucose during cooking. Showa Sangyo Co Ltd has launched low-calorie pasta named "Spaslim" which contains a mixture of glucomannan and ester alginate added to the flour. Apparently, 70 g of the modified pasta created the same sensation of fullness as 100 g of spaghetti but took twice as long to cook as ordinary spaghetti.

The promotion of satiety-inducing foods which are attractive to the consumer confronts the industry with a difficult challenge. The dilemma is that food products will need to be carefully designed to have an enhanced satiety factor without possessing the negative attribute of giving the consumer an abnormal or uncomfortable feeling of fullness.

8 Dietary fiber: carb or non-carb

During the last two years there has occurred one of the largest, sudden shifts in eating behavior in the USA in recent memory. The restriction on carbohydrate or carbs as they have become known, was triggered by a series of diet books, such as Atkins and South Beach Diet, that urge carb restraint. However, the low carb obsession emphasizes the importance of reducing the amount of digestible carbohydrates in a diet. Since dietary fibers are classified as non-glycemic, nondigestible carbs there is an argument that they should be excluded from the 'total carbohydrate' value [114]. In fact, in Australia and many European community countries, dietary fiber is not included in 'total carbohydrate'. Some companies want the FDA to follow this approach, change its rules governing the Nutrition Facts panel, and allow fiber content to be listed separately. This of course impacts directly on all the food products which use resistant starch in their formulations.

There is no question that the industry, particularly in the USA, has responded quickly to the low-carb phenomenon and a barrage of low carb products are on the market. It has definitely impacted on the sales of traditionally high-carb products like pasta, fruit juice, and bread. However, the impact is not so pronounced in Australia or the European community. The long-term strategy (if any) to cash in on the low-carb craze is difficult to envisage. Predictions that the low-carb diet is only a fad may have gained some credence as recent reports have stated that fewer than 10% of Americans are currently on low-carb diets and more than half of all consumers who have tried the diet have given it up [114].

9 Concluding comments

Food companies are turning to functional food products as a promising growth area and this emphasis has rekindled interest in one of the most hotly debated nutrients in the food industry – dietary fiber. There is increasing scope for exploiting the physicochemical and physiological attributes of a multitude of dietary fibers, the technological versatility of which has never been as great. Physiologically, fiber seems to have become a panacea for all ills, as publications report an increasing number of correlations which suggest it impinges positively on human health. Whether this bubble will burst or not, is not known but in the current climate it is likely that concerted action to promote dietary fibers by scientists, fiber suppliers, food companies, and legislative authorities will yield rich rewards for fiber manufacturers and innovative food companies for some years to come. For consumers it means at the very least an opportunity for a diet with a more balanced calorie intake and at best, an increased chance of a host of long-term health benefits.

Research will supply the knowledge that expands the horizons of the technological functionality and give greater substance to the health claims. Not all of this knowledge will be good news for the industry, as already there are contradictory data on the positive benefits of certain fiber fractions [115]. Future revelations based on basic research and clinical human studies are sure to provide some winners and losers in the fiber arena. The suppliers have a critical role in providing the range of dietary fibers for the diversity of applications, which the food companies wish to exploit. Unless a sustained supply of quality fibers is available, applications will not follow. Unless there are exciting applications, there will be no provision of fiber. The pressure to break this 'Catch 22' situation will come from a public prepared to pay extra for food products which promise a significant health benefit, without compromising the sensorial appeal of the product. Legislative bodies have an important role to play in providing the public with clear guidelines about the nature of dietary fiber. One of the definitions put forward by the Food Nutrition Board of the Institute of Medicine of the National Academies separated fiber into dietary fiber and functional fiber [116]. If accepted by legislative authorities this definition would be disastrous, throwing the public into confusion and making labelling practices for the food industry a nightmare [117, 118].

The renaissance of dietary fibers as important elements of a healthy diet has been accompanied by sophisticated technological developments in the food industry. Predictions are that the demand for nutraceuticals and functional food additives will continue to grow, stimulated by new products and an increasing number of health conscious consumers. Functional foods are definitely here to stay. However, to what extent products enriched in dietary fiber will contribute to sustained growth in this sector, depends on the results of research in validating the perceptions of the health benefits of dietary fiber and the efforts of the food industry in formulating and promoting products which carry these benefits to the consumer.

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