Review

Dietary fibre basics: Health, nutrition, analysis, and applications

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Abstract

Over the past decades, dietary fibre (DF) has been well studied with abundant evidence on its health benefits. Advances in nutritional studies always lead the way followed by the food applications. Food scientists and technologists then explored the applications of DF in a variety of food products through examination and utilization of fibres from various conventional and uncommon sources including agro-food processing by-products. However, the current intake levels of fibre and fibre-rich foods are still far below recommended values in most nations worldwide. In addition, research is needed to substantiate different mechanistic effects of intrinsic, intact fibres presented originally in the food matrix and the isolated, refined fibre added back to the novel food products. Standardized quantification methods for DF are needed for various reasons including broad range of sources, complicated chemical structures, and ever-changing definitions from various regulatory bodies. On the other hand, there are more consumer demands for clean labels or precise information on daily values (DV%), alongside more restricted regulations for certain nutritional claims such as ‘high fibre’. It is clear that all these demands create a practical pressure on professionals working in the food industry, particularly at quality assurance (QA) positions, on how to obtain reliable data from DF analysis to meet regulatory and labelling requirements. Fortunately, with the most recent Codex definition and advanced instruments that are capable to automate the analytical procedures and produce consistent results, it is foreseeable that global harmonization on DF studies can be achieved. Meanwhile, advanced processing technologies such as dry fractionation, enzymatic conversion, and micronization present promising opportunities for R&D professionals to advance the DF utilization and applications in functional food development.

Key words: dietary fibre; health benefits; technological functionality; fibre-mineral interaction; fibre analysis; label claims and regulations.

Introduction

Definitions and classification

The term ‘dietary fibre’ (DF) was first introduced in 1950s, referring to plant cell wall materials; later it was used to describe a class of plant-originated polysaccharides, which cannot be digested and absorbed in the gastrointestinal tract (van der Kamp, 2004). Over the past five decades, confusion existed in defining ‘DF’ and in classifying a large amount of substances under this umbrella term (Brownlee, 2011; Phillips and Cui, 2011a). Many scientific communities, such as the American Association of Cereal Chemists (AACC) and the Institute of Medicine (IOM) of the US National Academy, as well as food regulatory bodies including the US FDA, FAO/WHO Food Standards Program Codex Alimentarius Commission, and European Food Safety Authority (EFSA), have attempted to provide a clear definition for scientific and/or regulatory purposes. The various milestones in the evolution of ‘DF’ definition include the following highlights (Spiller, 2001; van der Kamp, 2004; Brownlee, 2011; Phillips and Cui, 2011a, 2011b):
Conventional classification of dietary fibres as soluble and insoluble fibres (Cho and Dreher, 2001; Chawla and Patil, 2010; Dai and Chau, 2016). A conventional classification of DF is based on water solubility (Table 1). Another approach for classifying the fibres in consumer food products is based on food applications and for the regulatory/labelling purpose. DFs can be categorized as ‘endogenous’ versus ‘added’ fibres, in which the former refers to intrinsic and intact fibres present in the original food matrix, while the latter being a group of fibres that are isolated from certain sources and added back to a product formulation. The latter is also called functional fibres, according to the IOM definition (Institute of Medicine (IOM), National Academy of Sciences, 2001): ‘Dietary fibre consists of non-digestible carbohydrates and lignin that are intrinsic and intact in plants. Added fibre consists of isolated, non-digestible carbohydrates that have beneficial physiological effects in humans. Total fibre is the sum of Dietary Fibre and Added and/or Functional Fibre’ (Phillips and Cui, 2011a).

Although there have been arguments in the research field of human nutrition concerning the physiological functionality of added/functional fibres in terms of whether they have same effects as opposed to the ‘endogenous’ fibres (Fardet, 2010; Kohn, 2016), numerous studies in the food science field have attempted to incorporate refined fibre powders isolated from various sources into food formulations, leading to novel functional products rich in fibre (Kunzek et al., 2002; Fernández-López et al., 2004; Borderías et al., 2005; Elleuch et al., 2011; Ktenioudaki and Gallagher, 2012; Macagnan et al., 2016).

**Research history and current status**

Although the DF research was initiated by human nutritionists and physicians, with the early work focusing more on its biomedical aspect, the topic has quickly attracted the attention from a wider range of scientific fields, including plant chemistry, food chemistry, food processing technology, nutritional biochemistry and pharmaceuticals. It is clear that ‘DF’ is no longer a topic for any single subject area; instead, it has become an inter-disciplinary research subject and requires close collaborations of expertise from a number of multiple discipline areas (Table 2).

The decades of 1970s and 1980s resulted in significant advancement in DF research, subsequently leading to a well-established research area. Some of the pioneering work in this period includes the ‘dietary fibre hypothesis’ proposed by Trowell and Burkitt (Spiller, 2001; Phillips and Cui, 2011a; Dai and Chau, 2016), which linked DF with its metabolic effects in terms of reduction in cardiovascular disease, diabetes, and certain cancers (Cui and Roberts, 2009; Kendall et al., 2010). In the last two decades before the new century, the majority of the research was still driven by physicians and human nutritionists with an effort in elucidating the mechanisms of DF’s health-promoting actions. Many clinical and epidemiological studies have led to dramatic increases in the body of knowledge and evidence that supports the protective role of DF in the prevention and management of chronic diseases (Kendall et al., 2010; Brownlee, 2011; Turner and Lupton, 2011; Academy of Nutrition and Dietetics, 2015).

Since 2000, food scientists and technologists have joined the research efforts in developing novel functional food products based on the advancement in clinical studies. Notably two approaches have been followed: the first one focuses on the full utilization of fibre-rich materials such as whole grains and fibre-rich by-products from fruit and vegetable processing (O’Shea et al., 2012); another direction is to extract and isolate fibre components from various sources (Fuentes-Zaragoza et al., 2010; Rastall, 2010; Torres et al., 2010). Some treatments may be applied to obtain refined fibre ingredients with modified technological functionalities (Mrabet et al., 2016; Wen et al., 2017). These refined fibre powders are then added into various food formulations as active ingredients or nutraceuticals, leading to fibre-enriched or fibre-fortified products (McCleary and Prosky, 2001; Cui and Roberts, 2009).

Upon surveying the literature, many critical reviews have been published in the most recent decade (2006–2016) concerning the inter-disciplinary advances of DF research, not to mention numerous articles reporting original research results from individual subject areas. Recent findings in clinical and epidemiological studies have been highlighted by several reviews (Flight and Clifton, 2006;
involve discussions on plant cell walls and derived materials for food products (McCleary and Prosky, 2001; van der Kamp, 2004; Tosh and Yada, 2010). Meanwhile, food scientists and technologists in academia and in the food industry have also conducted vigorous research in developing functional foods using fibre-rich raw materials or using isolated functional fibres. These progresses have been well documented in a number of comprehensive review articles (Kunzek et al., 2002; Fernández-López et al., 2004; Borderías et al., 2005; Chawla and Patil, 2010; Tosh and Yada, 2010; Elleuch et al., 2011; Macagnan et al., 2016). Other comprehensive reviews involve discussions on plant cell walls and derived materials for food applications, as well as for food quality improvement (Kunzek et al., 2002; Waldron et al., 2003).

Among the research efforts, a continuous, triennial conference—International Conference of Dietary fibre held in 2000, 2003, 2006, 2009, 2012, and 2015, respectively, has provided a great forum for researchers in this area to exchange, collect, and disseminate knowledge obtained through studies in a wide range of inter-disciplinary fields. Each of these six conferences resulted in a comprehensive proceedings/book containing the most updated information, with specific focuses on DF components and functions, advancement of analytical methods including both \textit{in vitro} and \textit{in vivo} measurements, new fibre sources and extraction/characterization methods, as well as utilization of DFs in food applications leading to novel food products (McCleary and Prosky, 2001; van der Kamp, 2004; Salovaara et al., 2007; van der Kamp et al., 2010).

All these achievements have collectively presented a much clearer picture of the current status on DF research, as well as a better-defined research scope; however, there is still some confusion. For example, the nutritionists raised a question—‘is dietary fibre considered an essential nutrient’ (Kohn, 2016). As pointed out by the author, ‘fibre is undoubtedly an essential part of a healthy eating plan, yet its implication as a nutrient has been somewhat elusive’. Unlike other essential nutrients, there are a wide range of compounds that qualify for the claims as DFs as opposed to a single one. Also, the absence of a deficiency state and an accurate estimation on average requirement prevents it from being considered as an essential nutrient. Although the nutritional community acknowledges the importance of DF in human health, they still argue if the added or functional fibre may present the same or equivalent biological or physiological performance as its original or endogenous form. Also, they suggested some incidence of gastrointestinal complaints and impaired absorption of certain nutrients due to potential interference of fibre is exclusively derived from functional fibre sources added to processed food formulations. Nonetheless, based on an overwhelming clinical evidence in relation to beneficial effects of DF in human health, food scientists and technologists have started to develop fibre-enriched or fibre-fortified novel products, primarily using isolated and purified fibre ingredients also known as functional fibre. There is clearly a need to link and coordinate the research efforts from individual areas in forming interdisciplinary teams to address and advance the DF research.

### Biological and Physiological Functionalities of DF

#### Health effects of DF

Health benefits of DF have been well documented in the literature over the past two decades. Diets, deficient in DF, lead to a number of diseases such as constipation, hiatus hernia, appendicitis, diabetes, obesity, coronary heart diseases, gallstones, etc. (Sudha et al., 2011). Consumption of adequate amounts of DF reduces the risk of above-mentioned diseases (Academy of Nutrition and Dietetics, 2015). Specifically, studies have shown that individuals with adequate intake (AI) of DF appear to be at lower risk for developing stroke (Zhang et al., 2013), colorectal cancer (Dahm et al., 2010; World Cancer Research Fund/American Institute for Cancer, 2011), cardiovascular diseases (Jiménez et al., 2008; Eshak et al., 2010; Ning et al., 2012; Threapleton et al., 2013), and type-2 diabetes

| Subject areas                              | Major progresses                                                                                           | References                      |
|--------------------------------------------|------------------------------------------------------------------------------------------------------------|---------------------------------|
| Before                                    | Physiological- botanical aspect                                                                         | Spiller, 2001; Cho and Dreher, 2001 |
| 1970s to 1980s                             | Human nutrition, Nutritional biochemistry                                                               | Spiller, 2001; Van der Kamp, 2004; Tosh and Yada, 2010 |
| 1980s to 1990s                             | Chemistry, Human nutrition                                                                             | Spiller, 2001; van der Kamp, 2004; Brownlee, 2011 |
| 1990s to 2000s                             | Chemistry, Human nutrition, Plant and food sciences                                                      | Spiller, 2001; van der Kamp, 2004; Tosh and Yada, 2010 |
| after 2000                                 | Chemistry, Human nutrition, Nutrigenomics, Plant science, Food processing technology, Consumer sciences | Spiller, 2001; Tosh and Yada, 2010; Dai and Chau, 2016 |

Johnson and Lund, 2007; Fardet, 2010; Kendall et al., 2010; Pryne et al., 2010; Viuda-Martos et al., 2010; Brownlee, 2011, in an effort to elucidate the mechanisms associated with the various physiological effects of DF in promoting human nutrition, including disease prevention and intervention. Fractionation of fibrous materials from various sources and characterization of individual fibre components have been reviewed based on oligosaccharides (Mussatto and Mancilha, 2007; Rastall, 2010; Torres et al., 2010), resistant starch (Fuentes-Zaragoza et al., 2010), pectin (Sila et al., 2009), gums (Phillips and Phillips, 2011), etc. Meanwhile, food scientists and technologists in academia and in the food industry have also conducted vigorous research in developing functional foods using fibre-rich raw materials or using isolated functional fibres. These progresses have been well documented in a number of comprehensive review articles (Kunzek et al., 2002; Fernández-López et al., 2004; Borderías et al., 2005; Chawla and Patil, 2010; Tosh and Yada, 2010; Elleuch et al., 2011; Macagnan et al., 2016). Other comprehensive reviews involve discussions on plant cell walls and derived materials for food applications, as well as for food quality improvement (Kunzek et al., 2002; Waldron et al., 2003).

The characterization and analytical methods were further advanced, and the research was active in linking the structure features of dietary fibre components to their physiologically functions, as well as in the exploration of under-utilized sources, extraction and preparation of refined fibres as active food ingredients.
(Meyer et al., 2002; Wannamethee et al., 2009; Ye et al., 2012; Cho et al., 2013; Yao et al., 2014). Increased intake of DF is also associated with lower blood pressure and lower serum cholesterol levels (Brown et al., 1999). In addition, AI of fibre is suggested to aid in weight loss or prevent weight gain, mainly through satiety or fullness regulation (Fairbanks et al., 2010; Mozaffarian et al., 2011; Wanders et al., 2011; Shay et al., 2012; Clark and Slavin, 2013; Li et al., 2014), and appears to improve immune function through gut health and fibre-microbiota interactions (Watzl et al., 2003; Simpson and Campbell 2015; Dong et al., 2016). In children, increased fibre intake has been found to be associated with lower risk of being overweight or obese (Choumenkovich et al., 2013; Quick et al., 2013).

By far, there is no doubt that solid health claims of DF can be derived from a large amount of clinical data; however, the detailed mechanisms that can elucidate these beneficial effects are still under investigation (Lattimer and Haub, 2010). The original definition of DF being non-digestible in the upper GI tract has limited the research focusing only on its fermentability in the colon, subsequently on its interactions as prebiotics with colonic microbiota. Recent studies have linked the health benefits of DF with a range of its functionalities in the upper GI tract (Mackie et al., 2016). Particularly, the increase in viscosity caused by high molecular-weight biopolymers in soluble fibre can alter gastric emptying thus the sensation of satiety and fullness, subsequently nutrient release and sensing in the duodenum. On the other hand, the interactions between insoluble fibre and colonic microbiota have been studied using modern rapid DNA sequencing technology (Simpson and Campbell, 2015), and it is suggested the fermentability of DF, in relation to the release of different levels of short-chain fatty acids (SCFAs), plays a critical role in the composition (diversity) and metabolic activity of the microbiome, which in turn affects the intestinal health and ultimately the immune system, subsequently the body’s ability to resist some chronic diseases.

The Academy of Nutrition and Dietetics of USA (2015) stated that ‘the public should consume adequate amounts of DF from a variety of plant foods’. Dietary Guidelines Advisory Committee (2015) recognizes DF as a shortfall nutrient and suggests its under-consumption in the general public, as in relation to adverse health outcomes, should be considered as a ‘public health concern’ (Kohn, 2016). Hence, daily recommended intake levels for DF in different age groups were proposed in 2010 and 2015 Dietary Guidelines for Americans (Academy of Nutrition and Dietetics, 2015; Kohn, 2016).

**Recommended Daily Intake for DF**

The National Center for Health Statistics (NCHS) conducted a study every 2 years within 1999–2008 to estimate the daily fibre intake of individuals and compare it with recommended intakes (National Center for Health Statistics [NCHS], 2010). Participants were aged 18 years and above. Data were collected through cross-sectional design using dietary recall interviews conducted in person by trained health professionals. The USDA 5-step Automated Multiple-Pass method was employed. Results indicated (Figure 1) that the mean daily intake of DF is stagnant at the level of 15 to 16 g per day per person. According to this study, the daily fibre intake has not progressed toward national goals during the past decade and the average Americans still do not meet the recommendation. Although there is no known deficient state of DF reported worldwide, it was first identified as ‘nutrient of concern’ for Americans in the 2005, and this categorization was reaffirmed in 2010 (USDA Dietary Guidelines for Americans, 2005; USDA Dietary Guidelines for Americans, 2010). Based on a 2009–2010 NHANES, the average intake of DF for Americans was 15 grams per day (Centers for Disease Control and Prevention [CDC], 2009). According to the 2010 Dietary Guidelines for Americans (DGA), the recommended AI levels for total fibre intake by age and gender are: 38 g per day for men aged 19 to 50 years, 30 g per day for men older than 50 years, 25 g per day for women aged 19 to 50 years, and 21 g per day for women older than 50 years. Thus, most individuals in the United States consume less than half of the daily recommended dietary intakes of DF.

Current dietary guidance directs consumers to increase intake of nutrient-dense and fibre-containing foods, yet emphasizes on maintaining energy balance over time to achieve and sustain a healthy weight (USDA Dietary Guidelines for Americans, 2010). To meet the daily fibre intake needs, the 2010 DGA recommends increased consumption of cooked dry beans and peas, vegetables, fruits, whole grains, and other foods with naturally occurring fibre. According to CDC survey (2009), 40% of people nationwide consume fruit and vegetables ≤ 2 times/day. The typical American meets only 42% (male) and 59% (female) of daily intake goals for fruits and vegetables (USDA Dietary Guidelines for Americans, 2010). In addition, the typical American eating pattern meets only 15% of the whole-grain goal, or < 28 g (1 oz) out of the recommended 85 g (3 oz-equivalents) per day. In fact, the mean daily intake level of total grains (primarily as refined flours from endosperm, not including bran) for Americans is 181 g or 6.4 oz per day, which is slightly higher than the recommended amount of 170 g (5.9 oz)/day for a 2000 kcal diet, whereas the average-whole grain intake is less than 28 g (1 oz)/day, which is even lower than one-third of the recommended amount, ≥ 85 g (3 oz)/day (CDC, 2009).

Based on the NHANES results, under 10% of the US population meets the recommended fibre intakes. Other countries also ingest well below the recommended amounts even if there is limited information from other nations (Jones, 2013). In order to meet the DF requirement with common foods, AIs of whole grain and fruit and vegetable along with nuts and legumes are recommended by the USDA’s MyPlate model (Clemens et al., 2012). The recently-updated Codex definition on DF provides opportunities for international harmonization to address this nutritional gap when all countries adopt the standardized quantification methods and regulatory definition for labelling (Dai and Chau, 2016).

**Technical Functionalities of DF in Food Applications**

Data suggest that more emphasis needs to be placed on consuming adequate amounts of fibre, whether from intrinsic source materials...
or from added fibre ingredients in formulated foods. This will help to close the gap between the actual intake status and the recommended fibre consumption. Regardless of the fibre source, either naturally occurring in foods or added during food reformulation and production, both forms become part of the total fibre content of the food according to IOM Dietary Reference Intake (Institute of Medicine (IOM), National Academy of Sciences, 2005). Similarly, fibre definitions from the AACC and Codex address appropriate DF intake without differentiation of amounts from naturally occurring or added fibres. Thus, it is logical that recommendations for obtaining fibre from foods should be inclusive of all types of fibre, both intrinsic and added.

Common source materials used as fibre ingredients

As suggested by dieticians and other nutrition practitioners, a healthy dietary pattern should include a variety of whole foods rich in fibres such as whole grains, fruits, vegetables, legumes, nuts and seeds, which will not only help to achieve the daily recommended amount for DF, but also to fulfill the needs for other important nutrients. Despite the fact that added or functional fibre may not yield the same benefits as naturally-occurring DF, it is generally agreed that all types of fibre can address the severe fibre consumption gap in existence throughout the world. Foods with added fibre can complement efforts to increase the intake of whole foods. Therefore, it is important to recognize that the combination of naturally fibre-rich and fibre-fortified foods can increase fibre intake and fibre variety while allowing consumers to stay within allowed energy levels (Jones, 2013).

Examples of functional fibres include inulin, beta-glucan, psyllium, and resistance starch, which are isolated and/or purified forms, and have been extensively studied in the development of novel functional foods with numerous publications (Table 3).

Recent advances in utilization of uncommon fibre source materials

Functional fibres that are derived from wheat, corn and rice have been commonly accepted in various food applications, both for their health attributes and technical functionalities. Besides these traditional fibre sources, there is a recent trend in the food industry by exploring the utilization of novel or uncommon sources of DF, specifically the by-products from processing of fruits, vegetables, legumes, and seeds (Table 4). These by-products, mainly consisting of peels or skins, stems and cores, are disposed of, usually at a cost to the producer via animal feed, landfill or incineration; thus potentially causing negative impacts on the environment. O’Shea et al., (2012) reviewed recent findings in the utilization of DF from fruit sources such as pomaces of apple, grape, lemon, mango, orange, and peach, as well as from vegetable sources including pomaces from carrot, cauliflower, onion, potato, and tomato. Elleuch et al., (2011) reviewed the methods for characterization of these fibre-rich by-products and the technological functionalities of these fibres when added into various food formulations. Many original research publications also report the properties and performance of these uncommon fibre sources in different food formulations (Table 4).

DF extracts/isolates obtained from different sources or based on different preparation methods have variations in their physico-chemical properties, leading to varying applications in food product development (Table 5). Specifically, Mrabet et al., (2016) reported the enzymatic treatment to convert insoluble fibre in dates to soluble fibre using Viscozyme® L, leading to a functional ingredient with increased antioxidant activity and higher concentrations of prebiotic oligosaccharides. Similarly, Wen et al., (2017) studied the effects of enzymatic treatment in combination of micronization on structural and functional properties of rice bran, resulting in a fine fibre powder with increased soluble-to-insoluble ratio, reduced water and oil holding capacity, increased swelling capacity, and improved absorption capacity for cholesterol and sodium taurocholate. With the modified or tailor-made properties, the functional fibres are open to a variety of promising applications in novel functional food development.

### Table 3. Types, effects, and sources of functional fibre ingredients used in food applications (Clemens et al. 2012).

| Isolated, modified or synthesized fibre in food applications | Main physiologic effects | Usually originated or derived from |
|-------------------------------------------------------------|--------------------------|----------------------------------|
| Beta-glucan and oat bran | Blood lipid lowering; attenuates blood glucose response | Oats and barley |
| Cellulose | Laxation | Plant foods |
| Chitin/chitosan | Blood lipid lowering | Fungi or shellfish |
| Guar gum | Blood lipid lowering; attenuates blood glucose response | Guar bean (legume) |
| Short-chain fructooligosaccharide, including inulin, oligofructose | Laxation; gut health; microbiota modulation toward a more healthful community; blood lipid lowering | Chicory root, Jerusalem artichoke |
| Galactooligosaccharide | Gut health; microbiota modulation toward a more healthful community; immune system modulation | Legume extract, Dairy products |
| Pectin | Blood lipid lowering; attenuates blood glucose response | Plant materials |
| Polydextrose | Laxation | Synthesized from dextrrose (glucose) |
| Psyllium | Laxation; blood lipid lowering; attenuates blood glucose response | Psyllium husk (plant) |
| Resistant dextrins | Blood lipid lowering; attenuates blood glucose response | Corn and wheat |
| Resistant starch | Laxation; gut health; attenuates blood glucose when substituted for digestible carbohydrates | Plant materials |
| Soluble corn fibre | Attenuates blood glucose response; gut health | Corn |
| Wheat bran | Laxation | Wheat |
Table 4. Common and novel sources of dietary fibres (Fernández-López et al. 2004; Flight and Clifton 2006; Tosh and Yada, 2010; Chawla and Patil, 2010; O’Shea et al. 2012).

| From cereal grains | By-products from fruit processing—peels or pomace | By-products from vegetables | By-products from legumes and seeds | Others |
|--------------------|-------------------------------------------------|-----------------------------|----------------------------------|--------|
| Rice bran, corn bran, wheat bran, barley, oat bran, psyllium husk, distiller’s grains | Apples (Rana et al. 2015), cherry (Basanta et al. 2014), plums (Sojka et al. 2015), oranges (Russo et al. 2015), papaya (Calvache et al. 2016), mangos (Ajila and Prasada Rao, 2013), lemons and lime (Rafiq et al. 2016), watermelon rinds and sharlyn melon peels (Al-Sayed and Ahmed, 2013), dates (Mrabet et al., 2016), kiwi, pears, grapefruits, pineapple, peaches, | Olives (Galanakis, 2011), potatoes (Jeddou et al. 2017), carrots, cauliflower, asparagus, tomatoes | Basil seed (Hajmohammadi et al. 2016), soybean hulls (Yang et al. 2014), peas, beans, peanut hulls, sunflower hulls, sesame coat/skin | Sugar beets, sugarcane, cocoa hulls |

Table 5. Treatment methods and impacts on technological functionality of fibres (McCleary and Prosky, 2001; Salovaara et al. 2007; Chawla and Patil, 2010; Mrabet et al. 2016; Wen et al. 2017).

| Modification approach | Means | Fibre source | Changes in technological functionality |
|-----------------------|-------|--------------|---------------------------------------|
| Chemical modification | pH    | Modified citrus pectin | Easy dissolution in fluids and better absorbed and utilized by the body |
| Mechanical treatment  | Alkaline (H₂O₂) Grinding | Rice straw | Increased water holding and oil binding capacity and swollen volume |
| Non-chemical treatment | High-pressure homogenization | Sugar beet pectin | Increased water holding/retention properties and fat absorption capacity |
|                       | High hydrostatic pressure (HHP) in combination with thermal treatment | Okara by-product from soybean | Enhanced emulsifying properties |
|                       |                                    |                                | Increased soluble fibre fraction, modified in vitro physiological functionality |

Preference is given to foods containing DF due to its benefits to human health. This attention has opened a great investment opportunity for the food industry to incorporate DF into a wide variety of food products (Bergman et al., 1994), such as breakfast cereals, breads, baked products, and pasta (Tudonica et al., 2002; Brennan et al., 2004; Petitot et al., 2010; Silva et al., 2013). However, manufacturers need to be careful about the fibre types and amounts added to their products because adding DF to foods creates alteration to the product formulation and can adversely affect the quality of many manufactured products, such as breads and other bakery goods, pasta and other extruded products (Chen et al., 1988; Bustos et al., 2011; Coorey et al., 2012).

Many studies have been conducted to evaluate the effect of adding different sources and levels of DF on various bakery products. For example, early study back in 1977 evaluated the effect of adding cellulose, wheat bran, and oat hulls as fibre sources on bread quality (Pomeranz et al., 1977). Findings indicated that final volume of breads was lower and the texture was less desired than fibre-free bread. Chen et al., (1988) evaluated the effect of added apple pomace fibre on the loaf volume in bread making. The results indicated that the addition of 4% hydrated apple fibre reduced loaf volume by 14%. Coorey et al., (2012) had also concluded that incorporating 15% chia seeds, a rich source of DF, made the dough very sticky and unable to be rolled thin enough for chip manufacturing. A recent study (Almeida et al., 2013) employed response surface methodology to examine the effects of fibre addition from different sources and at different levels on processing and quality parameters during the bread making. The authors reported some positive results, for example, the proofing time, crust colour and appearance acceptance, and taste and aroma acceptance, were not significantly affected by the fibre addition within the acceptable range; however, high-speed mixing time, crumb colour and appearance acceptance, and texture acceptance were influenced by the three different fibre sources studied, e.g., wheat bran, resistant starch, and locust bean gum. In addition, wheat bran resulted in some undesirable alterations on specific volume, crumb chroma and hue angle. In general, it is not very difficult to reformulate bakery products by incorporating high fibre contents from various sources; however, the main challenge is that such products are not widely accepted by the consumers (Ktenioudaki and Gallagher, 2012), due to major or minor alterations of sensory properties from fibre-enriched formulations compared to their reference products.

In addition to adverse effects of added fibre on bakery goods, it is also reported that formulating pasta with DF produces modifications that may cause some problems in the quality of the final product (Bustos et al., 2011). For example, Petitot et al., (2010) had examined the effect of incorporating high amounts of legume flour, split pea and faba bean flours into conventional pasta made with durum wheat semolina. It was reported that incorporation of high levels of DF required modifications to the pasta making process. Moreover, addition of legume flours led to a decrease in pasta quality attributes such as greater cooking loss and poorer texture property. Similarly, Brennan et al., (2004) evaluated the effect of adding inulin at different levels on the texture properties of fibre-enriched pasta made from semolina. Inulin was successfully used as a fat replacer in various food applications such as table spread, baked goods, fillings, dairy products, and dressings (Roberfroid, 2007; Raninen et al., 2011), though it caused negative effects on pasta cooking and texture quality. Another study (Silva et al., 2013) evaluated the effect of adding soluble and insoluble DFs (inulin, guar gum, pea fibre) on pasta quality characteristics. Results indicated that both type and amount of added fibres altered the overall quality of both raw and cooked pasta. Significant increase in cooking loss was reported in both inulin and pea fibre formulations. Texture attributes were also significantly degraded compared to the control pasta. Additionally, Kuar et al., (2012) reported that fortifying pasta with 20% of cereal bran had adversely affected the physicochemical, textural and.
A recent review article (Dai and Chau, 2016) compared these methods mainly from a classification and regulatory perspective. In general, these official methods can be categorized into enzymatic-gravimetric and enzymatic-chemical methods including colorimetric, gas-liquid chromatography (GLC) and high-performance liquid chromatography (HPLC) quantification. Enzymatic-gravimetric assays are relatively simple, inexpensive, fast, and robust enough for routine analysis; however, they do not provide detailed profiles for different DF components. Colorimetric assays in general require a reference method for reliable data interpretation due to the non-specific colour reactions of reducing sugars with chromogens. GLC or HPLC-based quantification assays, such as the most recent version of AOAC 2011.25/AACC 32–30.01, are more advantageous as the most inclusive one for determining all sorts of DF (Rainakari et al., 2016; Dai and Chau, 2016), and are ideal when a product contains unknown amount and type of fibre ingredients. However, these methods are very expensive and time-consuming, and also require high capital investments and highly trained personnel.

The first set of AOAC 985.29/AACC 32–05.01 standard method was officially adopted in 1985, and several modifications were introduced in 1986 and 1988, which is primarily limited to total DF analysis. From 1990 to 1991, further modifications were implemented to improve job efficiency and precision, and to reduce analytical costs, leading to the set of AOAC 991.43/AACC 32–07.01 official method, which can distinguish soluble and insoluble fibre from total fibre analysis. This assay is also designed to simulate the enzymatic digestion that occurs in the gastrointestinal tract of the human body. In spite of some limitations, this later set of the method has been widely accepted and proven to be robust enough in routine analysis tasks over the past two decades. Several disposable test kits have then been developed for quick determination in industrial QA/QC and R&D practice, yet is not sufficient for nutritional labelling purpose.

The AACC Approved Method 32–07.01 requires a series of enzymatic digestions with two changes in temperature and pH. Following three enzyme incubations, the IDF fraction is isolated by filtration through a vacuum-assisted filtering crucible with a diatomaceous earth filter mat. The filtrate is then mixed with heated ethanol to precipitate the SDF fraction. After waiting for flocculation to occur, the precipitated SDF is subsequently captured by a second filtration step. Both the IDF and SDF fractions captured in the filters are rinsed numerous times using heated water and/or ethanol. Throughout the method, eight different solutions are carefully measured and added to the sample. During the enzymatic digestion phase, the samples are continuously agitated at temperatures of 95°C and then at 60°C. This multi-step method requires technicians to perform more than 33 manual steps that include numerous transfers and filtration. Skilled technicians are required to ensure the process...
is done consistently and correctly. Plugged filters often waste time and energy. Some of the largest errors occur during the points where filters frequently plug and rinsing of the fibre is then incomplete.

Given that the current methods for determining DF involve numerous manual steps that take an extended period of time for skilful lab technicians to complete with acceptable accuracy and precision, there is significant interest in automating the process. The challenge of automation does not lie in the design of a system fully controlled by computer, instead, it is difficult to replicate the steps involving the observational judgements that are performed by technicians. For example, a quantitative transfer of a liquid/solid mixture from a beaker to a filter while drawing by a vacuum is a relatively simple task for a technician. Whether rinsing the wall of the beaker or adjusting the rate of vacuum relies on the observational judgement from a skilful technician. Engineers have not found a reliable way to replace the visual input of technicians for this task. Therefore, a completely different approach to solving the beaker and filtration issues was needed.

DF analysis has been performed by analytical chemists for more than 30 years. During this time, instruments have been developed that offer some improvements over standard glassware systems. These instruments have focussed on reproducing the conventional beaker and filtration process in a more compact and user-friendly system. However, they will require technicians to manually transfer liquids and use vacuum-assisted filtration. The benefits of such instruments to technicians is marginal. A fully automated instrument that performs the DF analysis without significant technician involvement has not been successfully accomplished until now. Toward this end, an automated instrument, Ankom Automated Dietary Fibre Analyzer, has been developed, in an effort to eliminate most of the labour-intensive aspects of the conventional method.

Ankom DF analyzer is a fully automated, self-contained benchtop unit that adheres to the specifications of the standard AOAC and AACC methods for DF analysis, and produces accurate and precise results in a relatively fast turnover time. Primarily based on enzymatic-gravimetric assay principle, specifically AOAC 991.43/AACC 32-07.01 method, the unit allows users to perform stand-alone insoluble dietary fibre (IDF), soluble dietary fibre (SDF), and total dietary fibre (TDF) analyses. With capability of capturing the filtrate for subsequent HPLC analysis, the unit can be upgraded to meet the newest AOAC 2009.01 and AOAC 2011.25 standards. The Ankom model is the first unit of its kind that adopts computer-aided multichannel pumps to automate the addition of chemical solutions, enzymes, and rinses. A design of dual-chambered vessel in the shape of a bag is used to maintain the flexibility while making the entire process convenient to handle. An upper reaction section and a lower filter section can be temporarily sealed to keep them separate. Once enzymatic incubation is completed the sample in the upper section can be easily transfer to the lower section, followed by IDF filtration and SDF precipitation and subsequent SDF filtration. With the aid of patented filter bag technology (Komarek, 1994), this unit increases filtering surface area and prevents frequent clogging issues, overall reduces the time needed and per sample cost, while providing increased accuracy and precision (Komarek, 1993; Komarek et al., 1994).

Multiple studies have been conducted to compare the performance of this unit to the results produced by following the reference method (Vogel et al., 1999; Wilman and Adesogan, 2000; Cherney, 2000; Thiex, 2008). The results produced by the instrument were in good consistence with the average reported from multiple laboratories using the reference standard (Komarek, 2012).

### Interrelationship between fibre’s biological and technological functionalities

As discussed above, DF has been studied from different subject areas: nutrition, chemistry, and food processing technology. Therefore, the properties of fibre and its fractionated components have been reported from different angles, i.e., physico-chemical properties, physiological effects, as well as technological functionalities (Table 6). The physico-chemical properties are more from the domain of chemistry and material science. Of course, their physiological properties or health-benefiting effects are more from the nutrition point of view. Technological functionalities or engineering properties are of interest from a food processing perspective. Ultimately, the materials’ physico-chemical properties are determinants for other functionality, either in the body, or during food processing. This is because only the materials’ physical and chemical properties are directly associated with the chemical structures. That is why the research has been focused more on the ‘structure-function relationship’ in the past decades: chemical composition and structure are the keys to rendering different functionality, no matter in the human body or in a food matrix.

Recent advances in analytical methods, specifically for assessments on physical, chemical, organoleptic properties of DFs, accelerates the understanding of structure-property relationship. Based on the accumulative scientific evidence from all related disciplines and extensive experience from the industrial practice over the past two

### Table 6. The properties of dietary fibre: material science-oriented physico-chemical properties, nutrition-oriented physiological effects, and food application-oriented technological functionalities

| Physico-chemical properties (material physics/chemistry) | Physiological effects (biomedical and nutritional area) | Technological functionality (food product/process development) |
|---------------------------------------------------------|--------------------------------------------------------|------------------------------------------------------------|
| Solubility                                              | Changes in intestinal function                         | Water binding/holding capacity                            |
| Viscosity                                               | Reduction of cholesterolema                         | Fat/oil binding and retention capacity                    |
| Density and bulk volume                                 | Modification of the glucemic response                 | Viscosity and rheological property                         |
| Surface area characteristics and porosity               | Laxation                                              | Gel-forming capacity and swelling                         |
| Particle size                                           | Satiety                                                | Fermentative capacity                                     |
| Cation exchange capability                              | Fermentation in the colon                            | Metal ion-chelating capacity                              |
| Chemical reactivity/interaction with other organic molecules including fat/oil, protein, vitamins, antioxidants | Reduction of nutrient availability                    | Texturizing capacity - thickening, bulking, texture modification |
|                                                         | Enhanced health benefit through synergistic effects with other active ingredients | Flavour modification                                      |
|                                                         |                                                        | Control of sugar crystallization                          |
decades on DF research, the better understanding of mechanisms will provide a systematic guidance for fibre utilization and applications in novel functional food development. As observed through this comprehensive literature survey, there are three trends in the current efforts of food product development when using various DF materials (Table 7): 1. using fibre-rich raw material as a whole in conventional food production, 2. using isolated, purified fibre ingredients for enrichment or fortification in unconventional food carriers, and 3. using processing waste stream or by-product as a source of DF along with other bioactive or phytochemicals left in the by-products. Each of the three trends has been reported with some promising results worth further investigation, while some technical challenges faced by food developers during their formulation design include:

- generally speaking, high level of recommended daily intake of DF cannot be easily achieved in a single formulation;
- impact of various DF sources at different addition levels on processing operation parameters, product quality and sensory properties is unpredictable;
- the effect of operation variations, esp. during the scale-up process from bench-top formulations to massive production using automated assembly lines may cause another level of technical issues for realizing the integrity, bioavailability, and palatability of fibre-fortified foods.

Knowledge Gaps in DF Research

With active research ongoing in this field and numerous promising results published in recent years, there are still some questions unanswered, specifically, with some evidence indicating the potentially negative effects from high fibre intake levels on mineral absorption/bioavailability, as well as reliable yet practical methods for fibre analysis so to allow the food producers to make proper claims under restricted regulations on DF.

Undesirable interactions of DF and minerals

Increased intake of DF may also cause a potentially negative effect on mineral absorption in the body (Idouraine et al. 1995). The addition of brans from oat and wheat to the diet of adult males resulted in decreased absorption rates for copper (Cu), calcium (Ca), magnesium (Mg), and zinc (Zn) (Moak et al., 1987). More results from animal studies confirmed that the addition of relatively high levels of DF in the rat diets resulted in impaired absorption of a number of key mineral elements such as iron, zinc, calcium, and magnesium (Donangelo and Eggum, 1986; Ward and Reichert, 1986). In addition to human and animal studies, in vitro research using controlled models supported the effect of DF on mineral bioavailability. For example, Claye et al. (1996) compared in vitro binding capacity of total DF versus fibre fractions present in wheat. Individual fibre components (lignin, hemicelluloses, and lignocelluloses) had selective binding effects on zinc, while a strong binding effect on copper was observed with total DF. DF presented in raw materials, such as brans of wheat, rice, and oat, have been demonstrated with in vitro binding effects on Ca, Mg, Zn and Cu, respectively (Idouraine et al., 1995). Treated fibres, such as dephtyhydrized insoluble fibre (DF fraction without phytate), have been also confirmed with mineral binding capacity at different levels (Gualberto et al., 1997).

Still under debate, DF inhibits mineral absorption, with a reason being that the mechanism of this interaction, particularly in processed products such as pasta, has not been well studied. Some researchers have postulated the underlying mechanism. Wong and Cheung (2005a, 2005b) have related the reducing effect of DF on mineral absorption in the body to one of the three following mechanisms: 1. shortened transit time when DF moves along the small intestine and thus reducing the time needed for mineral absorption; 2. directly impaired transportation of minerals when DF moves along the intestinal mucosal cells; and 3. chemical binding effect of DF on minerals in forming a mineral-fibre complex that cannot be broken down and absorbed in the body. The mineral-fibre complex might be generated during any of the food production, handling, and even consumption processes prior to arriving to the absorption site in the small intestine. Additionally, this binding effect can be complicated by numerous factors, not only associated with individuals’ nutritional status, meal pattern, and cooking/serve habit, but also related to the source, particle size, composition, and other physicochemical properties of DF when present or added into foods (van der Aar et al., 1983; Idouraine et al., 1995; Claye et al., 1998; Guillou and Champ, 2002; Sangnark et al., 2003). Specifically, particle size reduction of DF showed decreased tendency of in vitro binding effect on selected minerals (van der Aar et al., 1983; Sangnark and Noomhorm, 2003), which may open a potential way of processing fibre through micronization before using it as an ingredient in food formulations.

Table 7. Trends of dietary fibre utilization in novel food product development (McCleary and Prosky, 2001; Salovaara et al. 2007; van der Kamp et al. 2010).

| Approaches                                                                 | Food applications                                                                 |
|---------------------------------------------------------------------------|-----------------------------------------------------------------------------------|
| Use of fibre-rich raw materials containing intrinsic and intact fibre for conventional food production | Bread, breakfast cereals, pasta and noodles, bakery goods, extruded snacks         |
| Addition of isolated, purified fibre in non-traditional DF carriers for enrichment or fortification | Meat, fishery, and dairy products including fermented beverages                   |
| Utilization of processing waste stream or by-product rich in fibre for formulation improvement | Re-structured meat and fishery products, bread, extruded snacks                    |

DF analysis to meet regulatory and labelling purposes

Adding nutrients to foods to promote positive health benefits is a practice that is well accepted and has been successful in reducing nutrient deficiencies (Clemens et al., 2012). The 2010 DGA acknowledges that ‘fortified foods and supplements may be useful in providing one or more nutrients that otherwise might be consumed in less than recommended amounts’ (USDA Dietary Guidelines for Americans, 2010). The IOM acknowledges that consuming fibres from a variety of sources with the objective of increasing total fibre intake offers a number of health benefits. Growing recognition of the positive benefits of different types of fibres, both intrinsic and added, has contributed to a greater use of isolated fibres as food ingredients, which are incorporated in fortified foods, particularly staple foods made from cereal grains.

Based on the importance of whole grains and other added fibre ingredients many food manufacturers and processors have considered to reformulate their products using whole grain sources and to
invent new products with more fibre contents. USDA has recognized manufacturers’ efforts in increasing the consumer awareness of the importance of fibre through their new and reformulated products with added fibre sources (Garnett, 2004). According to current regulations, a food item can carry the claim of ‘more or added fibre’ when it contains at least 2.5 g of fibre per serving more than the reference food. A ‘good source of fibre’ claim can be made when the food contains 2.5 to 4.9 g of fibre, and a ‘high fibre’ claim can be made when a food item contains 5 g or more fibre per serving (Hazen, 2012).

As discussed in section 4.1, there are still some technical challenges in fibre analysis given its broad range of sources, complicated chemical structures, and ever-changing definitions from various regulatory bodies. On the other hand, there are more consumer demands for clean labels or precise information on daily values (DV%), alongside more restricted regulations for certain nutritional claims such as ‘high fibre’. It is clear that all these demands create a practical pressure to professionals working in the food industry, particularly at quality assurance (QA) positions, on how to obtain reliable data from DF analysis to meet regulatory and labelling requirements. Fortunately, with the most recent Codex definition and advanced instruments that are capable to automate the analytical procedures and produce consistent results, it is foreseeable that global harmonization on DF studies can be achieved (Dai and Chau, 2016), so to provide clear guidance on its applications in functional food development.

Conclusion and Perspectives

It is generally agreed that the current intake levels of fibre and fibre-rich foods are far below recommended levels in Western countries. Many health benefits of DFs are well documented. However, more research and evidence is needed to substantiate different effects between intrinsic, intact fibres presented originally in the food matrix and functional fibres produced during processing. Combining thermal and mechanical energies, extrusion process has been used to impart new functional properties, i.e., enhancing viscosity or gel forming ability. For example, extrusion cooking has been applied to food applications. Specifically, extrusion process has been used to test the changes of DFs in their physical properties and technical functionalities. Combining thermal and mechanical energies, extrusion process affects the chemical structure of DFs, and it may also impart new functional properties, i.e., enhancing viscosity or gel forming ability. For example, extrusion cooking has been applied to onion waste derived from the white outer fleshy scale leaves (Robin et al., 2012). After extrusion, an increase in solubility of the cell wall pectin polymers and hemicelluloses was observed along with swelling of the cell wall material, while carbohydrate composition of the cell wall material remained unaffected. With such modifications in solubility and apparent viscosity, the onion waste material can be used as a potential source of DF, leading to added values when applied to new formulations to produce extruded foods. Other food processing technologies such as dry fractionation (Wang et al., 2016), enzymatic conversion (Mrabet et al., 2016), and micronization (Wen et al., 2017) present promising opportunities in this area, ultimately to advance the DF utilization from various conventional and uncommon sources to address the nutritional gap faced by all populations in the world, when more clinical evidence also becomes available to further reveal the physiological and epidemiological mechanisms of DF in relation to human nutrition and public health.

References

Academy of Nutrition and Dietetics. (2015). Position of the academy of nutrition and dietetics: health implications of dietary fiber. Journal of The Academy of Nutrition and Dietetics, 115: 1861–1870.

Ajila, C. M., Prasada Rao, U. J. S. (2013). Mango peel dietary fiber: composition and associated bound phenolics. Journal of Functional Foods, 5: 444–450.

Almeida, E. L., Chang, Y. K., Steel, C. J. (2013). Dietary fibre sources in bread: Influence on technological quality. LWT - Food Science and Technology, 50: 545–553.

Al-Sayed, H. M. A., Ahmed, A. R. (2013). Utilization of watermelon rinds and sharlyn melon peels as a natural source of dietary fiber and antioxidants in cake. Annals of Agricultural Sciences, 58: 83–95.

Basanta, M. E., Escalada Pla, M. F., Raffo, M. D., Stortz, C. A., Rojas, A. M. (2014). Cherry fibers isolated from harvest residues as valuable dietary fiber and functional food ingredients. Journal of Food Engineering, 126: 149–155.

Bergman, C. J., Guallberto, D. G., Weber, C. W. (1994). Development of high-temperature-dried soft wheat pasta supplemented with cowpea (Vigna unguiculata L. Walp). Cooking quality, color, and sensory evaluations. Cereal Chemistry, 71: 523–527.

Borderias, A. J., Sánchez-Alonso, I., Pérez-Mateos, M. (2005). New applications of fibers in foods: addition to fishery products. Trends in Food Science & Technology, 16: 458–465.

Breman, C. S, Kuri, V., Tudorica, C. M. (2004). Inulin-enriched pasta: effects on textural properties and starch degradation. Food Chemistry, 86: 189–193.

Brown, L., Rosner, B., Willett, W. W., Sachs, F. M. (1999). Cholesterol lowering effects of dietary fiber: a meta analysis. American Society for Clinical Nutrition, 69: 30–42.

Brownlee, I. A. (2011). The physiological roles of dietary fiber. Food Hydrocolloids, 25: 238–250.

Bustos, M. C., Perez, G. T., Leon, A. E. (2011). Sensory and nutritional attributes of fiber-enriched pasta. Journal of Food Science and Technology, 44: 1429–1434.

Calvache, J. N., Caeto, M., Farray, A., de Escalada Pla, M., Gerschenson, L. N. (2016). Antioxidant characterization of new dietary fiber concentrates from papaya pulp and peel (Carica papaya L.). Journal of Functional Foods, 27: 319–328.

CDC. (2009). Average fruit and vegetable consumption per day nationwide. http://apps.nccce.cdc.gov/5ADaySurveillance/displayV.asp (accessed 4 December 2014).

Chawla, R., Patil, G. R. (2010). Soluble dietary fiber. Comprehensive Reviews in Food Science and Food Safety, 9: 178–196.

Chen, H., Rubenthaler, G. L., Kleung, H., Baranowski, J. D. (1988). Chemical, physical, and baking properties of apple fiber compared with wheat and oat bran. Cereal Chemistry, 65: 244–247.

Chenery, D. J. R. (2000). Chapter 14: Characterization of forages by chemical analysis. In: Grenwe D. I., Owen E., Axford R. F. E., Omel H. M. (eds.) Forage Evaluation in Ruminant Nutrition. CABI Publishing, Wallingford, UK, pp: 81–300.
Choy, S. S., Dreher, M. L. (2001). *Edited, Handbook of Dietary Fiber*. Marcel Dekker, Inc, New York, NY.

Choy, S. S., Qi, L., Fahey, G. C. J., Kurlerfeld, D. M. (2013). Consumption of cereal fiber, mixtures of whole grains and bran, and whole grains and risk reduction in type 2 diabetes, obesity, and cardiovascular disease. *American Journal of Clinical Nutrition*, 98: 594–619.

Choumenkovitch, S. F., et al. (2013). Whole grain consumption is inversely associated with BMI Z-score in rural school-aged children. *Public Health Nutrition*, 16: 212–218.

Clark, M. J., Slavin, J. L. (2013). The effect of fiber on satiety and food intake: a systematic review. *The Journal of the American College of Nutrition*, 32: 200–211.

Claye, S. S., Idouraine, A., Weber, C. W. (1998). In vitro binding capacity of five fiber sources and their insoluble components for copper and zinc. *Plant Foods for Human Nutrition*, 49: 257–269.

Claye, S. S., Idouraine, A., Weber, C. W. (1998). In vitro mineral binding capacity of five fiber sources and their insoluble components for magnesium and calcium. *Food Chemistry*, 61: 333–338.

Cleary, L., Brennan, C. (2006). The influence of a (1 → 3) (1 → 4)-β-D-glucan rich fraction from barley on the physico-chemical properties and in vitro reducing sugars release of durum wheat pasta. *International Journal of Food Science and Technology*, 41: 910–918.

Clemens, R., et al. (2012). Filling America’s fiber intake gap: summary of a roundtable to probe realistic solutions with a focus on grain-based foods. *Journal of Nutrition*, 142: S1390–S1401.

Coorey, R., Grant, A., Jayasena, V. (2012). Effects of chia flour incorporation on the nutritive quality and consumer acceptance of chips. *Journal of Food Research*, 1: 1927–1935.

Cui, S. W., Roberts, K. T. (2009). Dietary fiber: fulfilling the promise of added-value formulations. In: Kasapis, S., Norton, I. T., and Ubbink, J. B. (eds). *Modern Biopolymer Science*. Academic Press, London, pp. 399-448.

Dahm, C. C., Keogh, R. H., Spencer, E. A., Greenwood, D. C., Key, T. J., Fenieman, I. S., Rodwell, S. A. (2010). Dietary fiber and colorectal cancer risk: a nested case-control study using food diaries. *Journal of National Cancer Institute*, 102: 614–626.

Dai, F., Chau, C. (2016). Classification and regulatory perspectives of dietary fiber. *Journal of Food and Drug Analysis*, 25: 37–42.

Dietary Guidelines Advisory Committee. (2015). Scientific report, part A: executive summary. http://health.gov/dietaryguidelines/2015-scientific-report/PDFs/02-executive-summary.pdf (accessed 4 November 2015).

Donangelo, C. M., Eggum, B. O. (1986). Comparative effects of wheat bran and barley husk on nutrient utilization in rats. 2. Zinc, calcium and phosphorus. *British Journal of Nutrition*, 56: 269–280.

Dong, H., et al. (2016). Orange pomace fiber increases a composite scoring of subjective ratings of hunger and fullness in healthy adults. *Appetite*, 107: 478–485.

Ellrich, M., Bedigan, D., Rosieux, O., Bebsea, S., Blecker, C., Attia, H. (2011). Dietary fiber and fiber-rich by-products of food processing: characterization, technological functionality and commercial applications: a review. *Food Chemistry*, 124: 411–421.

Eshak, E.S., Iso, H., Date, C., Kikuchi, S., Watanabe, Y., Wada, Y. (2010). Dietary fiber intake is associated with reduced risk or mortality form cardiovascular disease among Japanese men and women. *Journal of Nutrition*, 140: 1445–1453.

Fardet, A. (2010). New hypotheses for the health-protective mechanisms of whole-grain cereals: what is beyond fiber? *Nutrition Research Reviews*, 23: 63–134.

Farinbanks, L. A., Blau, K., Jorgensen, M. J. (2010). High-Fiber diet promotes weight loss and affects maternal behavior in Vervet monkeys. *Journal of Primatology*, 72: 234–242.

Fernández-López, J., Fernández-Giménez, J. M., Aleson-Carboneill, L., Sendra, E., Sayas-Barberá, E., Pérez-Álvarez, J. A. (2004). Application of functional citrus by-products to meat products. *Trends in Food Science & Technology*, 15: 176–185.

Flint, L., Clifton, P. (2006). Cereal grains and legumes in the prevention of coronary heart disease and stroke: a review of the literature. *European Journal of Clinical Nutrition*, 60: 1145–1159.

Flores-Silva, P. C., Berrios, J. D., Pan, J., Osorio-Diaz, P., Bello-Perez, L. A. (2014). Gluten-free spaghetti made with chickpea, unripe plantain and maize flours: functional and chemical properties and starch digestibility. *International Journal of Food Science and Technology*, 49: 1985–1991.

Fuentes-Zaragoza, E., Riquelme-Navarrete, M. J., Sánchez-Zapata, E., Pérez-Álvarez, J. A. (2010). Resistant starch as functional ingredient: a review. *Food Research International*, 43: 931–942.

Galanakis, C. M. (2011). Olive fruit dietary fiber: components, recovery and applications. *Trends in Food Science & Technology*, 22: 175–184.

Garnett, S. C. (2004). Procurement service of whole grain products. http://www.fns.usda.gov/sites/default/files/2004-10-22.pdf (accessed 8 July 2014).

Guallart, D. G., Bergman, C. J., Weber, C. W. (1997). Mineral binding capacity of dephytinized insoluble fiber from extruded wheat, oat and rice brans. *Plant Foods for Human Nutrition*, 51: 295–310.

Guillon, F., Champ, M. (2002). Structural and physical properties of dietary fiber, and consequences of processing on human physiology. *Food Research International*, 33: 233–245.

Hajmohammadi, A., Pirouzifard, M., Shahedi, M., Alizadeh, M. (2016). Enrichment of a fruit-based beverage in dietary fiber using basil seed: effect of carboxymethyl cellulose and gum tragacanth on stability. *EWF · Food Science and Technology*, 74: 84–91.

Hazen, C. (2012). Fiber files. *Food Product Design*, 22: 1–6.

Hensel, K. (2015). Gluten-free without the sacrifice. *Food Technology*, 69: 21–31.

Idouraine, A., Hassani, B. Z., Claye, S. S., Weber, C. W. (1995). In Vitro binding capacity of various fiber sources for magnesium, zinc, and copper. *Journal of Agriculture and Food Chemistry*, 43: 1580–1584.

Institute of Medicine (IOM), National Academy of Sciences. (2001). *Dietary reference intakes: proposed definition of dietary fiber*. National Academy Press, Washington, DC.

Institute of Medicine (IOM), National Academy of Sciences. (2005). *Dietary reference intakes for energy, carbohydrate, fiber, fat, fatty acids, cholesterol, protein and amino acids*. National Academies Press, Washington, DC.

Jeddou, K. B., et al. (2017). Improvement of texture and sensory properties of cakes by addition of potato peel powder with high level of dietary fiber and protein. *Food Chemistry*, 217: 668–677.

Jiménez, J. P., et al. (2008). Effects of group of dietary fiber in cardiovascular disease risk factors. *Journal of Nutrition*, 24: 646–653.

Johnson, I. T., Lund, E. K. (2007). Review article: nutrition, obesity and colorectal cancer. *Alimentary Pharmacology & Therapeutics*, 26: 161–181.

Jones, J. M. (2013). Dietary fiber future directions: integrating new definitions and findings to inform nutrition research and communication. *Advances in Nutrition*, 4: 8–15.

Kendall, C. W. C., Esfahani, A., Jenkins, D. J. A. (2010). The link between dietary fiber and human health. *Food Hydrocolloids*, 24: 42–48.

Kohn, J. B. (2016). Is dietary fiber considered an essential nutrient? *Journal of the Academy of Nutrition and Dietetics*, 116: 360.

Komarek, A. R. (2012). Dietary fiber analysis: challenges of automation. *Cereal Food World*, 57: 50–54.

Komarek, A. R., Robertson, J. B., van Soest, P. J. (1994). A comparison of methods for determining ADF using the filter bag technique versus conventional filtration. *Journal of Dairy Science*, 77: 114.

Komarek, A. R. (1993). A filter bag procedure for improved efficiency of fiber analysis. *Journal of Dairy Science*, 76: 230.

Komarek, A. R. (1994). *Fiber Analysis System*. U.S. Patent No. 5,370,007. U.S. Patent and Trademark Office, Washington, DC.

Ktenoudaki, A., Gallagher, E. (2012). Recent advances in the development of high-fiber baked products. *Trends in Food Science & Technology*, 28: 4–14.

Kuzar, G., Shastna, S., Nagi, H. P. S., Das, B. N. (2012). Functional properties of pasta enriched with variable cereal brans. *Journal of Food Science and Technology*, 49: 467–474.

Kunzek, H., Müller, S., Vetter, S., Godeck, R. (2002). The significance of physic-chemical properties of plant cell wall materials for the development of innovative food products. *European Food Research and Technology*, 214: 361–376.
Laleg, K., Cassan, D., Barron, C., Prabhavasankar, P., Micard, V. (2016). Structural, culinary, nutritional and anti-nutritional properties of high protein, gluten free, 100% legume pasta. PloS One, 11: e0160721.

Lattimer, J. M., Haub, M. D. (2010). Effects of dietary fiber and its components on metabolic health. Nutrients, 2: 1266–1289.

Li, S. S., et al. (2014). Dietary pulses, satiety and food intake: a systematic review and meta-analysis of acute feeding trials. Obesity, 22: 1773–1780.

Macagnan, F. T., da Silva, L. P., Hecktheuer, L. H. (2016). Dietary fiber: the scientific search for an ideal definition and methodology of analysis, and its physiological importance as a carrier of bioactive compounds. Food Research International, 83: 144–154.

Mackie, A., Bajka, B., Rigby, N. (2016). Roles for dietary fiber in the upper GI tract: the importance of viscosity. Food Research International, 88: 234–238.

McClary, B. V., Prosky, L. (2001). Edited, Advanced Dietary Fiber Technology. Blackwell Science, Oxford.

Meyer, K. A., Kushi, L. H., Jacobs, D. R., Jr, Slavin, J., Sellers, T. A., Folsom, A. R. (2002). Carbohydrates, dietary fiber, and incident type 2 diabetes in older women. American Journal of Clinical Nutrition, 71: 921–930.

Moak, S., Pearson, N., Shin, K. (1987). The effect of oat and wheat bran fibers on mineral metabolism in adult males. Nutrition Reports International, 36: 1137.

Mozaffarian, D., Hao, T., Rimm, E. B., Willett, W. C., Hu, F. B. (2011). Changes in diet and lifestyle long-term weight gain in women and men. The New England Journal of Medicine, 364: 2392–2404.

Mrabet, A., et al. (2016). Enzymatic conversion of date fruit fiber concentrates into a new product enriched in antioxidant soluble fiber. J. Food Science and Technology, 75: 727–734.

Muscat, S. L., Mancilha, I. M. (2007). Non-digestible oligosaccharides: a review. Carbohydrate Polymers, 68: 587–597.

National Center for Health Statistics (NCHS). (2010). National Health and Nutrition Examination Survey Data. U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, Hyattsville. Available at https://www.cdc.gov/nchs/nhses/Nhans/SurveyOrientation/Navigate/Frame7.htm. Accessed February 2017.

Ning, H., Van Horn, L., Shay, C. M., Lloyd-Jones, D. M. (2012). Associations of dietary fiber intake with long-term predicted cardiovascular disease risk and C-reactive protein levels (from the National Health and Nutrition Examination Survey data (2005–2010)). The American Journal of Cardiology, 113: 287–291.

O’Shea, N., Arendt, E. K., Gallagher, E. (2012). Dietary fiber and phytochemical characteristics of fruit and vegetable by-products and their recent applications as novel ingredients in food products, Innovative Food Science & Emerging Technologies, 16: 1–10.

Petitot, M., Boyez, L., Minier, C., Micard, V. (2010). Fortification of pasta with split pea and fava bean flours: pasta processing and quality evaluation. Food Research International, 43: 634–641.

Phillips, A. O., Phillips, G. O. (2011). Biofunctional behavior and health benefits of a specific gum arabic - Review Article. Food Hydrocolloids, 25: 165–169.

Phillips, G. O., Cui, S. W. (2011a). An introduction: evolution and finalization of the regulatory definition of dietary fiber. Food Hydrocolloids, 25: 139–143.

Phillips, G. O., Cui, S. W. (2011b). AACR report: Definition of dietary fiber. http://www.aacnnet.org/news/pdfs/DFDef.pdf. (accessed 5 January 2011).

Pomerantz, Y., Shogren, M., Finney, B. F., Bechtle, D. B. (1977). Fiber in bread making: effects on functional properties. Cereal Chemistry, 54: 25–41.

Pryne, C. J., McCarron, A., Wadsworth, M. E. J., Stephen, A. M. (2010). Dietary fiber and phytate – a balancing act: results from three time points in a British birth cohort. British Journal of Nutrition, 103: 274–280.

Quick, V., Wall, M., Larson, N., Haines, J., Neumark-Sztainer, D. (2013). Personal, behavioral and socio-environmental predictors of overweight incidence in young adults: 10-yr longitudinal findings. International Journal of Behavioral Nutrition and Physical Activity, 10: 37.

Rafiq, S., Kaul, R., Sofi, S. A., Bashir, N., Nazir, F., Nayik, G. A. (2016). Citrus peel as a source of functional ingredient: a review. Journal of the Saudi Society of Agricultural Sciences, in press, available online 5 August 2016.

Available at https://www.scribd.com/document/135096185/Citrus-Peel-as-a-Source-of-Functional-Ingredient-A-Review. Accessed February 2017.

Rainakari, A., Ruta, H., Putkonen, T., Pastell, H.H. (2016). New dietary fiber content results for cereals in the Nordic countries using AOAC 2011.25 method. Journal of Food Composition and Analysis, 51: 1–8.

Rana, S., Gupta, S., Rana, A., Bhushan, S. (2015). Functional properties, phytonutrient contents and antioxidant potential of industrial apple pomace for utilization as active food ingredient. Food Science and Human Wellness, 4: 180–187.

Raninen, K., Lapps, J., Mykkänen, H., Poutanen, K. (2011). Dietary fiber type reflects physiological functionality: comparison of grain fiber, inulin, and polydextrose. Nutrition Reviews, 69: 21–29.

Rastall, R. A. (2010). Functional oligosaccharides: application and manufacture. Annual Review of Food Science & Technology, 1: 305–339.

Roberfroid, M. B. (2007). Inulin-type fructans: functional food ingredients. Journal of Nutrition, 137: 2493–2502S.

Robin, F., Schuchmann, H. P., Palzer, S. (2012). Dietary fiber in extruded cereals: limitations and opportunities. Trends in Food Science & Technology, 28: 23–32.

Russo, M., Bonaccorsi, I., Inferrera, V., Dugo, P., Mondello, L. (2015). Underestimated sources of flavonoids, limonoids and dietary fiber: availability in orange's by-products. Journal of Functional Foods, 12: 150–157.

Salovaara, H., Gates, F., Tenkanen, M. (2007). Edited, Dietary Fiber Components and Functions. Wageningen Academic Publishers, Wageningen, The Netherlands.

Sangnak, A., Noomhorm, A. (2003). Effect of particle sizes on in vitro calcium and magnesium binding capacity of prepared dietary fibers. Food Research International, 36: 91–96.

Shay, C. M., Van Horn, L., Stamer, J. (2012). Food and nutrient intakes and their associations with lower BMI in middle-aged US adults: the international study of macro/Micronutrients and blood pressure (INTERMAP). American Journal of Clinical Nutrition, 96: 483–491.

Sila, D. N., van Buggenhout, S., Duvetter, T., Fraeye, L., de Roeye, A., van Loey, A., Hendrickx, M. (2009). Pectins in processed fruits and vegetables: part II—structure–function relationships. Comprehensive Reviews in Food Science and Food Safety, 8: 86–104.

Silva, E., Sagis, L. M. C., Van der Linden, E., Sholten, E. (2013). Effect of matrix and particle type of rheological, textural, and structural properties of broccoli pasta and noodles. Journal of Food Engineering, 119: 94–103.

Simpson, H. L., Campbell, B. J. (2015). Review article: dietary fiber-microbiota interactions. Alimentary Pharmacology & Therapeutics, 42: 158–179.

Sloan, E. (2015). Predicting pasta’s potential. Food Technology, 69: 17.

Sokja, M., Kołodziejczyk, K., Milala, J., Abadash, M., Vittas, I., Goyou, S., Baron, A. (2015). Composition and properties of the polyphenolic extracts obtained from industrial plum pomaces. Journal of Functional Foods, 12: 168–178.

Spiller, G. A. (2001). Edited, CRC Handbook of Dietary Fiber in Human Nutrition, 3rd edn. CRC Press, Boca Raton, FL.

Sudha, M. L., Rajeswari, G., Venkataseswara-Rao, O. (2011). Effect of wheat and oat brans on the dough rheological and quality characteristics of instant vermicelli. Journal of Texture Studies, 43: 195–202.

Sudha, M. L., Leelavathi, K. (2012). Effect of blends of dehydrated green pea flour and amaranth seed flour on the rheological, microstructure and pasta making quality. Journal of Food Science and Technology-Mysore, 49: 713–720.

Thix, N. (2008). Evaluation of analytical methods for the determination of moisture, crude protein, crude fat, and crude fiber in distillers dried grains with solubles. Journal of AOAC International, 92: 61–73.

Threapleton, D. E., Greenwood, D. C., Evans, C. E. (2013). Dietary fiber intake and risk of cardiovascular disease: systematic review and meta-analysis. BMJ British Medical Journal, 347: 68797.

Torres, D. P. M., Gonçalves, M. P. E., Tenxera, J. A., Rodrigues, L. R. (2010). Galacto-oligosaccharides: production, properties, applications, and significance as prebiotics. Comprehensive Reviews in Food Science and Food Safety, 9: 438–454.

Tosh, S. M., Yada, S. (2010). Dietary fibers in pulse seeds and fractions: characterization, functional attributes, and applications. Food Research International, 43: 450–460.
Tudorica, C. M., Kuri, V., Brennan, C. S. (2002). Nutritional and physicochemical characteristics of dietary fiber enriched pasta. *Journal of Agricultural and Food Chemistry*, 50: 347–356.

Turner, N. D., Lupton, J. R. (2011). Dietary fiber. *Advances in Nutrition*, 2: 151–152.

USDA Dietary Guidelines for Americans. (2010). *Dietary guidelines for Americans*, 7th edn. US Government Printing Office, Washington, DC.

USDA Dietary Guidelines for Americans. (2005). *Dietary Guidelines for Americans*, 6th edn. US Government Printing Office, Washington, DC. www.health.gov/dietaryguidelines/dga2005/document/pdf/DGA2005.pdf (accessed 18 July 2014).

van der Aar, P. J., Fahey, G., Rickie, S. C., Allen, S. E., Berger, L. L. (1983). Effects of dietary fiber on mineral status of chicks. *Journal of Nutrition*, 113: 653–661.

van der Kamp, J. W. (2004). *Edited, Dietary Fiber – Bio-active Carbohydrates for Food and Feed*. Wageningen Academic Publishers, Wageningen, The Netherlands.

van der Kamp, J. W., Jones, J., McLeary, B. V., Topping, D. J. (2010). *Edited, Dietary Fiber: New Frontiers for Food and Health*. Wageningen Academic Publishers, Wageningen, The Netherlands.

Viuda-Martos, M., López-Marcos, M. C., Fernández-López, J., Sendra, E., López-Vargas, J. H., Pérez-Álvarez, J. A. (2010). Role of fiber in cardiovascular diseases: a review. *Comprehensive Reviews in Food Science and Food Safety*, 9: 240–258.

Vogel, K. P., Pedersen, J. F., Masterson, S. D., Toy, J. J. (1999). Evaluation of a filter bag system for NDF, ADF, and IVDMF forage analysis. *Crop Science*, 39: 276–279.

Waldron, K. W., Parker, M. L., Smith, A. C. (2003). Plant cell walls and food quality. *Comprehensive Reviews in Food Science and Food Safety*, 2: 128–146.

Wanders, A. J., et al. (2011). Effects of dietary fiber on subjective appetite, energy intake and body weight: a systematic review of randomized controlled trials. *Obesity Reviews*, 12: 724–739.

Wang, J., Suo, G., de Wit, M., Boom, R. M., Schutyser, M. A. I. (2016). Dietary fiber enrichment from defatted rice bran by dry fractionation. *Journal of Food Engineering*, 186: 50–57.

Wannamethee, S. G., Whincup, P. H., Thomas, M. C., Sattar, N. (2009). Associations between dietary fiber and inflammation, hepatic function, and risk of type 2 diabetes in older men: potential mechanisms for the benefits of fiber on diabetes risk. *Diabetes Care*, 32: 1823–1825.

Ward, A. T., Reichert, R. D. (1986). Comparison of the effect of cell wall and hull fiber from canola and soybean on the bioavailability for rats of minerals, protein and lipid. *Journal of Nutrition*, 116: 233–241.

Watzl, B., Gorbach, S., Roller, M. (2005). Inulin, oligofructose and immunomodulation. *British Journal of Nutrition*, 93: S49–S55.

Wen, Y., Niu, M., Zhang, B., Zhao, S., Xiong, S. (2017). Structural characteristics and functional properties of rice bran dietary fiber modified by enzymatic and enzyme-micronization treatments, *LWT - Food Science and Technology*, 75: 344–351.

Wilman, D., Adesogan, A. (2000). A comparison of filter bag methods with conventional tube methods of determining the in vitro digestibility of forages. *Animal Feed Science and Technology*, 84: 33–47.

Wong, K. H., Cheung, P. C. K. (2005a). Dietary fibers from mushroom Sclerotia: 1. preparation and physicochemical and functional properties. *Journal of Agriculture and Food Chemistry*, 53: 9395–9400.

Wong, K. H., Cheung, P. C. K. (2005b). Dietary fibers from mushroom Sclerotia: 2. in vitro mineral binding capacity under sequential simulated physiological conditions of the human gastrointestinal tract. *Journal of Agriculture and Food Chemistry*, 53: 9401–9406.

World Cancer Research Fund/American Institute for Cancer. (2011). Continuous update project report: food, nutrition, and physical activity and the prevention of colorectal cancer. http://www.dietandcancerreport.org/cancer_resource_center/downloads/cu/Colorectal-Cancer-2011-Report.pdf (accessed 8 October 2014).

Yang, J., Xiao, A., Wang, C. (2014). Novel development and characterization of dietary fiber from yellow soybean hulls. *Food Chemistry*, 161: 367–375.

Yao, B., Fang, H., Xu, W. (2014). Dietary fiber intake and risk of type 2 diabetes: a dose response analysis of prospective studies. *European Journal of Epidemiology*, 29: 79–88.

Ye, E. Q., Chacko, S. A., Chou, E. L., Kugizaki, M., Liu, S. (2012). Greater whole-grain intake is associated with lower risk of type 2 diabetes, cardiovascular disease, and weight gain. *Journal of Nutrition*, 142: 1304–1313.

Zhang, A., Xu, G., Liu, D., Zhu, W., Fan, X., Liu, X. (2013). Dietary fiber consumption and risk of stroke. *European Journal of Epidemiology*, 28: 119–130.

Zhao, Y. H., Manthey, F. A., Chang, S. K. C., Hou, H. J., Yuan, S. H. (2005). Quality characteristics of spaghetti as affected by green and yellow pea, lentil, and chickpea flours. *Journal of Food Science*, 70: S371–S376.

Zhu, F., Du, B., Zheng, L., Li, J. (2015). Advance on the bioactivity and potential applications of dietary fiber from grape pomace. *Food Chemistry*, 186: 207–212.