Hindawi
Journal of Chemistry
Volume 2017, Article ID 9340427, 8 pages
https://doi.org/10.1155/2017/9340427

Review Article

Modification and Application of Dietary Fiber in Foods

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Received 5 December 2016; Revised 31 January 2017; Accepted 28 February 2017; Published 8 March 2017

Academic Editor: Qingbin Guo

Dietary fiber plays an important role in human health. The modification and application of dietary fiber in foods is reviewed with respect to definition and classification and methods for measurement, extraction, and modification of dietary fiber. The supplementation of dietary fiber for flour, meat, and dairy products is also reviewed. Finally, the benefits and risks of increasing consumption of dietary fiber are discussed.

1. Introduction

With the improvement of the standard of living, people's diet has become increasingly sophisticated. Many lifestyle diseases are caused by an imbalanced diet, such as diabetes, cardiocerebrovascular disease, obesity, intestinal cancer, constipation, and other disorders that have serious adverse effects on the health of human beings. Therefore, functional foods that can adjust the body function and prevent lifestyle diseases of civilization have attracted more attention in recent years. Dietary fiber has outstanding health promotion functions [1]. In this review, we describe our current knowledge on these aspects of dietary fiber: definition, determination, extraction, modification, and application.

2. Definition and Classification

The compositions of dietary fiber may be complicated, and detection methods have not been standardized. In the middle of the 20th century, the term "dietary fiber" was first used by Hipsley to refer to plant components that resist being decomposed by endoenzymes secreted by mammalian cells [2]. In the 1970s, the phrase "dietary fiber" was used by Trowell, to describe indigestible carbohydrates [3]. Currently, dietary fiber is defined as nonstarch polysaccharide that cannot be absorbed by humans or digested by enzymes in the human gastrointestinal tract [4]. These polysaccharides include cellulose, noncellulosic polysaccharides such as hemicellulose, pectic substances, gums, mucilage, and a noncarbohydrate component, and lignin [5]. It is important to note that the composition of dietary fiber cannot be completely determined, and the concept of dietary fiber will likely continue to evolve [6]. There have been recent suggestions that the oligosaccharides known as resistance oligosaccharides should also be considered dietary fiber [7, 8].

Dietary fiber plays a very important role in regulation of human bodies [9]. This material is not able to be decomposed in the human gut and affects the moisture absorption in the digestive system. It can increase the volume of food inside the intestines and stomach, increase satiety, and facilitate weight loss [10]. Dietary fiber can promote gastrointestinal peristalsis to alleviate constipation [11] and absorb the harmful materials in the gut, promoting their removal [12, 13]. Additionally, dietary fiber can improve the intestinal flora and provide energy and nutrition for probiotics proliferation [14]. Recent studies have shown that dietary fiber helps to reduce postprandial blood glucose, insulin, and triglyceride concentrations [15, 16] and can lower blood cholesterol levels [17, 18]. Decreased concentrations of faecal bile acids are correlated with reducing cancer risk [19–21].

Dietary fiber can include soluble dietary fiber (SDF) and insoluble dietary fiber (IDF). SDF refers to fibers that cannot be digested or absorbed by human bodies but are partly soluble in water. Examples of SDF are some gums, such as pectin, gum Arabic, guar gum, and glucan, and also include some biological polysaccharides and synthetic polysaccharides. IDF is a fiber that cannot be digested or absorbed by human bodies and is insoluble in water. IDF includes some components of the structure of cell walls, such as cellulose, hemicellulose, and lignin. Many scholars classify dietary fiber according to the source, emphasizing that the compositions of dietary fibers extracted from different sources are different. Dietary fiber includes plant dietary fiber, synthetic dietary fiber, animal dietary fiber, and microbial dietary fiber. Current studies on dietary fiber have mainly focused on plant dietary fiber, such as dietary fiber from soybean, rice bran, corn, wheat bran, fruit, and other sources. Additional sources will be exploited gradually; for example, there is a report of spent residue from cumin as a potential source of dietary fiber [22]. The dietary fibers obtained from different sources differ in total dietary fiber content, SDF content, physicochemical properties, and physiological properties [23].

3. Measurement and Extraction Methods

The measurement methods for dietary fiber are varied. Based on the emphasis, there are methods to determine the amount of dietary fiber, including Weende analysis, and solvent and enzymatic methods to determine the components of dietary fiber, such as chemical analysis and instrumental methods [24].

Weende analysis began in the early 19th century, and this method is still used in many factories to determine the fiber in foods and fodder. More recently, the crude fiber method has been used but is less widely utilized. In this method, dilute acid and dilute alkali are mixed with raw materials and subjected to continuous heating and boiling reaction until only the residue left is crude fiber, but crude fiber makes up only a small part of dietary fiber. During the acid-base reaction, hemicellulose and lignin loss will occur, so the results do not truly reflect the total fiber in food but are a rough indicator. With the development of the chemical industry, solvent methods have been developed for the measurement and extraction of dietary fiber from foods. The solvent method uses an appropriate solvent to remove protein and starch, leaving fiber as the remaining residue, mainly insoluble fiber. The solvent methods are divided into different methods, according to the use of different solvents, such as for alcohol insoluble fiber extraction, the neutral detergent method, or an acidic detergent method, for example. These various methods result in differing measurements. The disadvantage of these solvent methods is that there can be different degrees of damage to the fiber during processing by the solvent, which will affect the result of the measurement. However, current methodologies, in particular the approved method of analysis of the Association of Official Analytical Chemists 3207 991.43, are sufficient for many foods. Some foods require additional methods for quantification of the dietary fiber levels in foods, if they contain fructans (polymers and oligomers of fructose or inulin), modified dextrins, and/or synthetic dietary fiber analogues [25]. Enzymatic methods are also used to determine and extract dietary fiber. Enzymatic methods use enzymes to remove protein and starch, allowing the content of dietary to be obtained after drying and weighing. For example, enzymatic determination uses pepsin to remove protein to determine water-insoluble dietary fiber and uses pancreatin to remove polysaccharide. Modifications have been made to improve these methods. For instance, McCleary et al. used the Enzymatic-Gravimetric Method to determine high-molecular-weight dietary fiber (HMWDF), using Liquid Chromatography for low-molecular-weight dietary fiber (LMWDF). These methods provide results that are comparable to other official dietary fiber methods, and this method is recommended for adoption as Official First Action [26]. Chemical analysis is generally used to determine the components of dietary fiber, and is often combined with enzymatic methods by using enzymatic treatment to remove the starch and using anhydrous ethanol for precipitation to obtain total dietary fiber. The Fibertec tester (Sweden Tecator Company) and HPLC can be used to determine the composition of dietary fiber by chemical analysis. HPLC is a relatively mature method and shows good repeatability and high precision [27]. FT-IR spectroscopy can also be used to determine fruit dietary fiber composition [28].

Extraction can include dry processing, wet processing, chemical, gravimetric, enzymatic, physical, and microbial methods, or a combination. Different treatment methods have different effects on dietary fiber structure. The use of acid and alkali treatment will damage the molecular structure of the fiber, but the use of enzymatic approaches may result in incomplete extraction [29, 30]. Instead, a combination of enzymatic and solvent methods is usually used for the extraction of dietary fiber. For example, in the extraction of wheat bran dietary fiber, running water is first used to remove impurities such as dust and adherent starch in the wheat bran. 2% NaOH is added and then neutral proteinase removes the protein, resulting in relatively pure dietary fiber. Recent research has focused on the use of emerging technologies (ultrasound, microwave, and high pressure processing) for extraction to improve the fiber yield and also to maintain or enhance its functionality. These methods may reduce processing times and temperatures and optimize the usage of solvents [31, 32].

4. Modification

Modification methods are used to transform IDF into SDF for better physicochemical and physiological properties [33]. Modification methods include mechanical degradation, chemical treatment, enzymatic, and microbiological fermentation methods. Typically, a combined method may have greater effects than any single approach. For example, chemical-enzymatic, ultrasound-enzymatic, and microwave-enzymatic modification methods have been described.

4.1. Mechanical Degradation Treatment Method. Mechanical degradation treatment includes extrusion cooking, high pressure, heating, or novel technology to mechanically disrupt the fiber. This review describes current knowledge of the use of extrusion cooking technology, instantaneous high pressure, and ultrahigh pressure treatment.

4.2. Extrusion Cooking Technology. Extrusion cooking technology subjects material to high temperature, high pressure, and high shear force, causing the internal moisture of the material to gasify quickly and extend and modify the fiber intermolecular and intramolecular spatial structure. At the moment of extrusion, the molecular structure of material is changed and forms a porous state. Studies have shown that extrusion cooking had a positive effect on total and soluble dietary fiber. The insoluble dietary fiber decreased appreciably with the varying processing parameters, probably due to disruption of covalent and noncovalent bonds in the carbohydrate and protein moieties leading to smaller and more soluble molecular fragments [34]. Additionally, the water solubility index was greatly enhanced by varying extrusion temperature and screw speed [35]. Some scholars used extrusion cooking technology-twin-screw extrusion to extract soluble dietary fiber from soybean residue. After a serial of orthogonal experiments, the optimum extrusion parameters were determined to be an extrusion temperature of 115°C, feed moisture of 31%, and screw speed of 180 rpm. Under these experimental conditions, the soluble dietary fiber content of soybean residue was 12.65%, 10.60% higher than the unextruded soybean residue. In addition, the dietary fiber in the extruded soybean residue had higher water retention, oil retention, and swelling capacity [36]. Another kind of modification method is blasting extrusion processing, and this method has great effect on dietary fiber modification. Chen et al. used blasting extrusion processing to modify the dietary fiber of bean dregs and found that, after extrusion modification at 170°C with an extrusion screw speed of 150 r/min, soluble dietary fiber content was increased by 27% [37].

4.3. Instantaneous High Pressure and Ultrahigh Pressure Treatment. Instantaneous high pressure treatment is performed using a high velocity jet homogenizer (microfluidizer) at pressures up to 300 MPa. Because the material quickly passes through the reaction chamber, the material is only briefly subjected to the high pressure and materials are ultra-micro-powderized. This treatment method was developed recently and allows even heating with low electricity costs. Liu et al. studied the use of instantaneous high pressure for soybean dreg dietary fiber and found significantly increased soluble dietary fiber content after treatment. Additionally, the physical characteristics (expansibility, water holding capacity, water-binding ability, and specific surface area) of the modified dietary fiber were different from those of the unmodified dietary fiber [38, 39].

Ultrahigh pressure treatment modifies raw material in an ultrahigh pressure reaction chamber in a certain time [40]. Wennberg and Nyman studied the use of ultrahigh pressure technology for Chinese cabbage SDF modification [41], and other scholars used this method to modify the dietary fiber of food like potato and apple. Ultrahigh pressure treatment can improve the content of soluble dietary fiber and its physicochemical properties and physiological characteristics. For example, Li et al. studied use of ultrahigh pressure for sweet potato residue IDF and found that the pressure, time and temperature of treatment had significant effects on blood sugar, blood fat regulation, and the capability of removing exogenous harmful substances. The optimal modification conditions by ultrahigh pressure for the ability to regulate blood sugar and blood fat were 600 MPa, 15 min, and 60°C. The treatment conditions for better removal of exogenous harmful material were 100 MPa, 10 min, and 42°C [42].

4.4. Chemical Method. Chemical methods use chemical reagents such as acid and alkali to break down dietary fiber. By controlling the amount of acid and alkali materials and the temperature and reaction time, some IDF is converted into SDF, with improved physiological characteristics. A recent study finds that hydrogen peroxide can improve the content of SDF in black soybean hull by about 10% and this material showed good ability of conjugating bile acid [43]. Carboxymethylation is also frequently used as a method of chemical modification and affects dietary fiber. A study reported improved SDF for dietary fiber extracted from whole grain barley by carboxymethylation [44]. Although chemical modification can improve the content of SDF, some chemical reagents may damage the molecular structure of the dietary fiber, reducing conversion efficiency or the physiological activity of dietary fiber.

4.5. Enzymatic and Microbial Fermentation Modification. Biological methods may be more environmental-friendly and healthy compared with other methods and include enzymatic and microbial fermentation. Enzymatic modification uses enzymes to degrade the dietary fiber, decreasing IDF and improving SDF. Enzymatic reactions use mild reaction conditions and have strong specificity. Additionally, there is typically little destruction of the composition and structure of the fiber, and this method does not result in chemical pollution, for high usability for the food industry. Enzymes used in dietary fiber modification are mainly xylanase, cellulose, and lignin oxidase. There are ongoing efforts to improve the enzymatic method. One study showed that using enzymes to hydrolyze bean dregs results in dietary fiber with higher biological activity and higher SDF is higher yield [45]. Some scholars used an enzymatic method to extract insoluble dietary fiber from *Dioscorea batatas* Decne residue and suggested that the method could improve the widespread use of Dioscorea [46].

Microbial fermentation uses organic acids and enzymes produced naturally by microorganisms to reduce the molecular weight and improve the solubility of dietary fiber. There are many sources of microbes and they are easily available. Nakajima et al. used fan anaerobic bacteria isolated from human faeces and showed that the bacteria can secrete an enzyme that can degrade fiber to generate oligosaccharides [47]. Another study reported that a filamentous fungus named CIsl6 has a significant effect on improving total dietary fiber and soluble dietary fiber of citrus dregs.

4.6. Mixed Treated Method. A combination of chemical, mechanical, enzymatic, and microbial fermentation methods to modify dietary fiber often allow better experimental results than the use of the single methods. For instance, Zong-Cai et al. reported that using microbial fermentation alone improved the content of SDF by more than 15%, but the use of microbial fermentation followed by microfluidization resulted in 35% SDF, and the resulting dietary fiber modified by this hybrid method showed higher physiological activity. Additionally, performing fermentation first can reduce the homogeneous processing difficulty and economize the homogenization energy. [48]. There are many other hybrid methods of modifying dietary fiber, such as micronization technology combined with enzymatic modification and high hydrostatic pressure-enzyme treatment [49]. For instance, ultrasonic-assisted enzymatic extraction of soluble dietary fiber from pomelo peel was recently investigated by Tang et al. The modified dietary fiber showed better antioxidant activity [50].

5. Applications

Epidemiological studies have reported that the consumption of foods that are rich in dietary fiber may reduce the risk of cardiovascular diseases, various types of cancer, and type 2 diabetes and possibly improve body function regulation. At the same time, huge quantities of food processing by-products are generated and not utilized, creating considerable environmental pollution if not properly disposed. If these by-products could be used as a dietary fiber source, it would reduce pollution and add value [51]. Many foods with added dietary fiber have been introduced. At present, dietary fiber application research mainly includes addition of dietary fiber to flour products, meat products, and dairy products or use as additives [5].

5.1. Dietary Fiber Application in the Flour Products. Currently, flour products that are rich in dietary fiber are widely available. Compared with nonmodified food, this kind of improved dietary product has attracted consumer interest and is sold for higher prices. The dietary fiber is often added in flour products, such as whole grain bread, noodles, biscuits, and steamed bread.

In Asian countries, noodles constitute an integral part of the diet. Noodles are processed from refined wheat flour [52]. Fiber-rich noodles sold in markets are usually made by adding bran, rather than soluble dietary fiber. The use of partially hydrolyzed guar gum, as a soluble fiber source, has been tested for use in fiber-fortified noodles with health benefits. The effect of soluble fiber level (1–5 g/100 g of flour) was investigated by Mudgil et al. and shown to have a significant effect on hardness, adhesiveness, and cohesiveness of noodles [53]. Attempts have been made by scientists to improve the nutritional properties of food products [54] and improve the value of by-products of food processing [55]. Banana peel (BP) is a coproduct produced in large volumes annually by food-processing industries. Its disposal is of significant concern, but recent research suggests that BP is a valuable source of bioactive compounds [56, 57]. A recent research showed that the noodles with added banana flour, rich in dietary fiber, had good nutritional quality and sensory acceptability [58]. A similar finding was found for improving quality of chapatti using banana peel powder as dietary fiber source [59]. Wheat bran as a rich source of dietary fiber can be added into noodles and steamed bread. Researches show that when the added content of DF is 5%–10%, noodles with higher quality are produced [60].

Many other dietary fiber sources have been found and used in food processing. For instance, coffee grounds were added to cookies for increased dietary fiber source, resulting in more nutritious and more flavorful cookies with potential value in the prevention of diabetes [61]. Protein/fiber-enriched cake with good sensory quality was produced by the substitution of wheat flour by 5% of potato peel powder [62]. Dietary fiber has also been applied into other flour products. For example, De Delahaye et al. studied addition of soluble and insoluble dietary fiber into spaghetti noodles [63]. Another study found that addition of dietary fiber into pizza dough improves taste and allows 60 days storage at 18°C [64].

5.2. Dietary Fiber Application in the Meat Products. Meat is often a core part of daily meals, and consumption of meat products with good quality is important for a healthy diet. The primary importance of meat as food lies in the fact that it is a good source of high biological value protein and provides essential fatty acids, vitamins, minerals, and many essential micronutrients. However, most meat is deficient in essential dietary fiber. Thus, to improve the nutritional value, attempts have been made to add dietary fiber from different sources into sausages, surimi, meatballs, meat emulsion, and other meat products.

Fiber addition in meat products is becoming more common, and dietary fiber addition may effectively increase acceptability by giving meat products higher quality, improving the processing characteristics of meat products, improving the yield of meat products, and lengthening the shelf time [65, 66]. Sausage is a representative meat product, and if the fat in it is too high it may have adverse health effects. Dietary fiber has been used as a fat substitute and added into sausages [67]. Mendes and others found that adding dietary fiber from wine production into sausages may improve nutritional value [68]. The effects of pineapple dietary fibers were also tested for effects on the physical, chemical, and textural attributes of sausage which were investigated with different observed effects for the kind of fiber added [69]. Sausages made with oatmeal have different cooking yield and hardness, which may be due to the water-retention properties of different meats in response to heat treatment [70]. Scientists have made different attempts to add dietary fiber into other meat products to improve their quality. Addition of dietary fiber into meat emulsion can lower cooking loss and improve emulsion stability and viscosity [71], and dietary fiber may be correlated with the rheological properties of meat emulsion [72].

5.3. Dietary Fiber Application in the Dairy Produce. Yogurt is made of fresh milk that is fermented with bacterial cultures and is considered as a healthy food. Yogurt with better taste and higher nutritional value has a higher acceptability. The physical attributes of yogurts, including the lack of visual whey separation and perceived viscosity, are crucial aspects of the quality and overall sensory consumer acceptance of yogurt [73]. Recent studies find that addition of dietary fiber may improve the nutritive value, but adding different amounts of dietary fiber into yogurt can influence texture, consistency, rheological properties, and consumer acceptability [74, 75]. For instance, Hashim et al. added different proportions of date fiber (DF; 0, 1.5%, 3.0%, 4.5%), a by-product of date syrup production into yogurt, or added 1.5% wheat bran (WB) into yogurt. Comparison of control yogurt with the yogurt showed that DF addition had a significant effect on yogurt acidity, and yogurt fortified with DF had firmer texture and darker color. Yogurt fortified with up to 3% DF had similar sourness, sweetness, firmness, smoothness, and overall acceptance ratings as the unmodified yogurt. The sensory ratings and acceptability of yogurt decreased significantly for 4.5% DF or 1.5% WB. Adding vanilla to yogurt fortified with 4.5% DF did not improve flavor or overall acceptance ratings. Thus, fortifying yogurt with 3% DF produced acceptable yogurt with beneficial health effects [76]. Goat milk is an excellent source of amino acids, fatty acids, and minerals and is widely used for processing fermented milks, such as yogurt. However, compared with cow milk yogurts, it is difficult to make goat milk yogurts with a good consistency. The fiber-rich pulp of Cupuassu (*Theobroma grandiflorum*) has different consistency than other fruit pulps. A recent study showed that adding Cupuassu (*Theobroma grandiflorum*) pulp into goat's milk for yogurt results in better consistency, texture, and higher nutritional value [77].

6. Development Prospect

Current tools to measure dietary fiber have low accuracy, and different measurements produce different results for dietary fiber content in food. For example, the dietary fibers of dried alga *Ulva lactuca* collected from the Tunisian littoral region were determined by the Prosky (gravimetric) and Englyst (enzymatic-chemical) methods. The two extraction methods resulted in approximately the same value of total fibers (54%) but had different insoluble and soluble fiber contents [78]. Therefore, improved measurement strategies are needed. Because different types of dietary fiber have different effects, a more precise definition of dietary fiber that describes composition and physical structure may be required [79].

The main extraction method for dietary fiber is chemical method, as this approach is easy, inexpensive, and easily applied for industrial production. However, the use of chemical reagents to extract dietary fiber may affect the physicochemical properties of the finer and could impact the resulting physiological benefits. The use of chemical reagents will also produce industrial wastewater that poses threats to the environment. In view of this, countries like the US and Japan are actively studying more eco-friendly extraction methods such as enzymatic method, membrane filtration, and fermentation. These extraction methods of dietary fiber are still in early development, and this is an important direction of future research.

Compared with IDF, more SDF is needed. Currently, there are no standards for the modification of dietary fiber. Industrial production of modified dietary fiber is still being developed. Future research is required for improved strategies to produce dietary fiber that is more suitable for the human body and to determine appropriate guidelines for dietary fiber intake. Previous studies of modified dietary fiber start with extraction, followed by modification, resulting in significant losses. If modification can be performed before extraction, these losses may be significantly decreased.

The stability of food can be obviously improved by adding dietary fiber into beverages. Dietary fiber may be added to food as a kind of additive agent. Dietary fiber can improve human health, but additional clinical studies are needed to determine the benefits and appropriate dosages.

7. Conclusion

Dietary fiber plays an important role in human health, with confirmed physiological benefits. However, some scientists and nutritionists believe that the benefits are overly exaggerated, and there may be confusion for consumers as to what they really need. Dietary fiber can prevent the absorption of harmful substances but will also prevent the absorption of proteins, inorganic salt and some minerals in food, a problem for people who need more of these nutrients, such as actively growing teenagers. Some people with intestinal tract disease may react poorly to supplementation with dietary fiber, resulting in irritation for the gastrointestinal tract. Better tools will elucidate the definition and physical properties of dietary fiber [80] and allow improved and more accurate determination of dietary fiber. Future methods for the extraction and modification of dietary fiber will be needed for large-scale industrial production. There are reports that supercritical CO_2 affects pear pomace insoluble dietary fiber physicochemical properties. For example, the glucose adsorption capacity and glucose retardation index of IDF were significantly higher after supercritical CO_2 treatment [81]. Additional studies are needed to expand the application of dietary fiber and improve its economic and practical value. Future work by nutritionists and scientists is also needed to determine the requirements for dietary fiber intake and to guide consumption of dietary fiber supplements.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

The present research was financially supported by Henan Province Colleges and Universities Young Backbone Teacher Plan (2016GGJS-070), Key Scientific and Technological Project of Henan Province (172102110008), Opening Foundation of Province Key Laboratory of Transformation and Utilization of Cereal Resource in Henan University of

Technology (24400036), and Support Program for the Natural Science Foundation of China in Henan University of Technology (31401035).

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