Proceedings of the 4th International Conference on Biological Engineering and Medical Science
DOI: 10.54254/2753-8818/57/20241255

Research on the functional properties and extraction methods of dietary fiber

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Abstract. Dietary fiber is a form of polysaccharide that does not yield energy and cannot be fully broken down and absorbed by the digestive enzymes in humans. Furthermore, the human body is unable to produce it; instead, food produced from plants is the only source of it. There are specific species of gut microbiota that ferment dietary fiber, producing short-chain fatty acids, monosaccharides, and gases as byproducts. Dietary fiber has both physicochemical (solubility, viscosity, absorption, water holding capacity, and oil holding capacity) and functional properties (glucose adsorption, cholesterol adsorption, and nitrite ion adsorption). Dietary fiber can be extracted from plant using a variety of techniques, including chemical, mechanical, and enzymatic methods; however, these techniques have significant shortcomings, such as narrow extraction zones and poor extraction quality. Through the course of the last few centuries, the amount of dietary fiber has significantly decreased, which has led to unhealthy human conditions like obesity, cancer, type 2 diabetes, and constipation. Nowadays, these Dietary fibers, therefore, are given great attention because of their physicochemical and functional properties which are vital for human health. These products from plant resources and fruits can be further used for food manufacturing and processing.

Keywords: Dietary fiber; physicochemical properties; functional properties; type 2 diabetes; intestinal health

1. Introduction

Dietary fibre(DF) is a complex polysaccharide of plant origin that is not hydrolysed endogenously in the small intestine, but is totally or partially fermented by the intestinal microflora in the large intestine. The major source of dietary fibers is extracted from whole grains, vegetables, fruits, and legumes. Dietary fibre promotes the health of the gastrointestinal tract by regulating its composition and metabolism, providing energy to the colonic epithelium, stimulating fibre synthesis, promoting peristalsis and maintaining the integrity of the intestine [1]. Furthermore, dietary fiber can also manage weight by increasing bulk to the diet. In terms of cardiovascular diseases and diabetic patients, dietary fiber can reduce absorption of glucose and regulate blood pressure to decrease the incidence of heart disease.

When dietary fibre is broken down by the intestinal microbiota, short-chain fatty acids (SCFA) such as acetic acid, propionic acid and butyric acid are produced, as well as gases such as methane and carbon dioxide [2]. SCFAs are absorbed by the colon, muscles, liver and other tissues and provide the body

DOI: 10.54254/2753-8818/57/20241255

with basic energy in the form of nutrients. Acetic acid facilitates the production of ATP through the citric acid cycle [3].

In recent decades, people have become more aware of nutrition and health. At the same time, it has been recognized that dietary fibre plays an important role in human nutrition and in the fight against chronic diseases. In addition, most people's daily intake of DF cannot meet the requirements of the Dietary Guidelines for Chinese residents, and most Americans consume less than half the recommended daily intake of DF; the daily intake of DF can be as little as 1/3 to 1/2 of the intake recommended in the dietary guidelines [4]. Dietary fiber, therefore, is extracted from plants to be utilized in diet as functional food. This involves chemical, physical and biological processes that can break down glycosidic bonds to a certain extent.

2. Classification and sources of dietary fiber

2.1. Classification of dietary fiber

Dietary fibers are the edible portions of plants and their extracts, as well as synthetic substitutes that are frequently fermented in the large intestine to some extent rather than being absorbed and digested in the small intestine [5]. Based on its solubility, dietary fiber is often divided into two categories: soluble dietary fiber (SDF) and insoluble dietary fiber (IDF). Dietary fibers are also divided into plant fibers and animal fibers, depending on their origin, while plant fibers are divided into cereal fibers, fruit fibers and vegetable fibers [2].

2.1.1. Soluble dietary fiber. Non-starch polysaccharides, or SDFs, are found in plant cytosol and interstitial fluid and are soluble in water. They can be fermented by the microbiota in the human gut and are typically derived from cereals, fruits, and vegetables [6], such as legumes, vegetables, pectin-resistant dextrin, and psyllium. Simultaneously, the gut microbiota in the human colon has the ability to ferment and breakdown SDF, producing a large number of SCFAs, which are viscous and can form a gel, delaying gastric emptying time and thus reducing cholesterol storage [7].

2.1.2. Insoluble dietary fiber. IDF refers to non-starch polysaccharides that cannot be dissolved in water or fermented by human gut microbiota, accounting for 2/3 to 3/4 of natural fibers, and are often found in plant roots, stems, trunks, leaves, skins, and fruits [6]. IDF is contained within common diets like enoki mushrooms, carrots, and oats, and the functional properties of different foods vary according to their IDF composition and structure [8]. What's more, IDF absorbs water in the large intestine to soften the feces and increase their volume, thereby preventing constipation [9].

2.2. Sources of dietary fiber

"The scientifically validated study of polymers of novel carbohydrates carried out by the Chinese Society of Nutrition in 2021, through the search and integration of databases and standards, declared that the sources of dietary fiber are of 3 types: naturally occurring in plants; obtained by extracting from plants by physical, chemical, and enzymatic methods; and obtained by synthesis [10]." Natural dietary fiber can be found in a variety of foods, including but not limited to fruits, vegetables, and grains. Dietary fiber-rich foods include wheat bran, citrus fiber, pea fiber, oat fiber, and beet fiber [10]. Cereal is considered a significant dietary fiber source due to its high content of insoluble dietary fiber (IDF). Moreover, cereal-based sources of dietary fiber have been found to have greater efficacy in regulating blood glucose levels when compared to alternative sources. There are 10 types of extracted and synthetic dietary fibers recommended by the Chinese Nutrition Society, which are galactooligosaccharides, fructooligosaccharides, inulin, polydextrose, β-glucans, cellulose, resistant maltodextrin, alginate, guar gum, and pectin [10].

DOI: 10.54254/2753-8818/57/20241255

3. Physicochemical and functional properties of dietary fiber

3.1. Physicochemical properties

The structural characteristics of dietary fibers are the basis of their physicochemical properties, which subsequently have a substantial impact on their functional capabilities. It frequently exhibit a flaky or flocculent, with folds and pores on the surface, some with small particles on the surface, and those with a loose structure, many folds, large pores, and low surface roughness, therefore, having better physicochemical properties [11]. Dietary fibers possess several physical and chemical characteristics mainly contain ion exchangeability, hydration qualities, oil holding capacity, adsorption capacity and solubility.

3.1.1. Hydration capacity. Dietary fiber, as a class of polysaccharides, has hydrophilic groups such as hydroxy(-OH) and carboxy(-COOH) in its chemical structure, and because of the physical structure of the particles on its surface, it has strong hydration capacity. The hydration properties of dietary fibers cause them to absorb water and swell when entering the body, increasing their volume and the weight of faeces to promote constant intestinal peristalsis, and shortening intestinal transit time and reducing intestinal exposure to secondary bile acids and other toxins [12]. It helps prevent gastrointestinal diseases such as constipation and rectal cancer.

3.1.2. Absorption. Dietary fiber molecules have a certain length, strength, and elasticity, and in the digestive tract of the body can form a mesh structure with a certain strength and volume, in which the mesh structure has physical adsorption properties [13]. The substance has the ability to bind and adsorb various chemicals, resulting in a deceleration of fat and carbohydrate absorption. Additionally, it promotes the excretion of bile acid, so exhibiting hypoglycemia and hypocholesterolemic effects [14]. In addition, dietary fiber has the ability to absorb certain toxic and detrimental constituents found in food, such as nitrite ions and heavy metals, hence mitigating the associated health risks [15]. Among them, natural dietary fibers have a strong adsorption capacity for fats, which is enhanced when treated, e.g., the adsorption capacity of saturated and unsaturated fats used in the experiments reached 6.53g/g and 3.16g/g, respectively, after ultramicrotomisation of soybean skin water IDF [16].

3.1.3. Ion exchange capacity. The ion exchange capacity of dietary fiber refers to the fact that in aqueous solution dietary fiber contains side chain groups like hydroxy(-OH) and carboxy(-COOH) can be reversibly exchanged with certain cations and adsorption of the original cations in the solution, mainly including Cu^{2+}, Pb^{2+}, Cd^{2+}, etc., and preferentially exchanges toxic heavy metal ions, such as Pb^{2+} and Cd^{2+}, so that they can be discharged from the body [17].Furthermore, it has the capacity to modify the immediate ion concentration, influence the pH level, redox potential, and osmotic pressure within the gastrointestinal system, and provide a buffer milieu that is more favorable for the processes of digestion and absorption [18].

3.1.4. Oil holding capacity. The oil holding capacity (OHC) of a material refers to the amount of oil it can absorb per unit of weight. The determination is made by submerging the sample in surplus oil and subsequently centrifuging the liberated oil [19]. OHC plays a crucial role in food applications, such as preventing fat loss and stabilizing food emulsions during food processing, as well as lowering serum cholesterol levels by absorbing fats and oils from the intestinal tract and excreting them after consumption [20].

3.1.5. Viscosity. Some dietary fibers can form a gelatinous state and are viscous, with the amount of viscosity depending on their chemical structure, with cellulose, lignin, etc., being almost non-viscous, but pectin, gum, agar, etc., usually having a strong viscosity [18]. The viscosity of dietary fibers is influenced by their molecular weight, chemical composition, water retention capacity, particle size, dissolving temperature, processing time and pH [2]. The characteristic of dietary fiber extends beyond

DOI: 10.54254/2753-8818/57/20241255

its application as a thickening agent in food preparation. For instance, pectin, a type of natural polysaccharide characterized by its intricate structure, serves as a crucial constituent of plant cell walls. It can also be used as a thickener, emulsifier, stabilizer, and other food additives widely used in the food production industry [21]. Viscose polysaccharides exhibit a beneficial impact on the reduction of blood glucose and blood cholesterol levels, while concurrently enhancing the enzymatic activity inside the digestive tract [22].

3.2. Functional properties

3.2.1. Prevention of cardiovascular disease. After a long period of experimental research by scientific researchers, a large amount of clinical data has proved that elevated serum cholesterol levels are one of the causes of coronary heart disease [18]. Therefore, sufficient consumption of dietary fiber has the potential to decrease the binding and adsorption of cholesterol, descent its absorption by the body, thus lowering blood pressure and lipid levels and preventing cardiovascular diseases. Previous studies have demonstrated that individuals who consume the largest amount of dietary fiber exhibit notably reduced rates of cardiovascular disease morbidity and mortality. These advantageous outcomes can perhaps be attributed to the capacity of dietary fiber to decrease levels of total serum and low-density lipoprotein cholesterol (LDL) [23]. Foreign scholars organized experimental population intake of arabinoxylan, which is common in cereals, analyzed serum cytokines of the experimental personnel and conducted metabolomics and genomics studies on them. The results showed that LDL decreased significantly after dietary fiber intake, and the value of bile acid, which helps to lower cholesterol, increased significantly [24].

3.2.2. Prevention and treatment of type 2 diabetes. Type 2 Diabetes Mellitus (T2DM) is a chronic metabolic disease in which patients mainly manifest high blood glucose, a relative lack of insulin, insulin resistance, dyslipidemia, etc. If no attention is paid to it and the condition is allowed to deteriorate, it may lead to a variety of complications. Mild symptoms include blurred vision, dizziness, headache, weakness, and difficulty in recovering from wounds; more serious complications, and potentially life-threatening diabetic nephropathy (DN) and cardiovascular disease [25]. Current research suggests that dietary fiber may regulate human blood glucose levels through the following three mechanisms: (1) dietary fiber may regulate human glucose metabolism, by inhibiting the digestion and absorption of sugary foods and accelerating their metabolic rate, etc.; (2) dietary fiber may regulate insulin activity, by improving insulin resistance, regulating the release of insulin, and controlling the expression of key genes, etc.; (3) dietary fiber has the potential to exert an impact on the growth and metabolism of the intestinal microbiota, alter the metabolites produced by the gut microbiota, and regulate the ionic environment and pH levels within the intestines. Consequently, it may assume a regulatory function in the progression of diabetes [26, 27]. Dietary fiber infiltrates the gastrointestinal tract and acquires a thick consistency, impeding the absorption and utilization of glucose and prolonging the time it takes for the stomach to empty, hence ensuring consistent blood glucose levels following meals [28]. A considerable body of research has demonstrated that adequate consumption of dietary fiber has the potential to decrease postprandial blood glucose levels in individuals with diabetes, as well as mitigate the likelihood of developing chronic conditions such as glucose intolerance [29, 30]. Furthermore, insulin is produced via insulin cells in healthy individuals, and its primary role is to facilitate the decomposition of blood glucose and the production of glycogen for storage, while also regulating blood glucose levels within a specific range. However, in individuals with diabetes, the impaired insulin cells are unable to produce an adequate amount of insulin, resulting in reduced glycogen synthesis and impaired glucose storage, ultimately leading to elevated blood glucose levels. But dietary fiber can absorb water and become viscous, slowing down the decomposition and absorption of glycogen, thus controlling blood glucose levels in a safe range, and also increasing the sensitivity of glycogen to stimulate insulin secretion [28]. On the other hand, the microbiota of T2DM patients is characterized by a decrease in the consumption of Short Chain Fatty Acid (SCFA), a decrease in the abundance of SCFA, changes in the intestinal flora,

DOI: 10.54254/2753-8818/57/20241255

impairment of the intestinal barrier function, and an increase in the level of plasma Lipopolysaccharide (LPS) [31]. Hence, high-fiber diets, low-carbohydrate diets, and Mediterranean diets, which substitute high-fat, high-sugar, low-dietary-fiber diets by advocating for a substantial consumption of fruits, vegetables, and legumes, have demonstrated the ability to elevate the intestinal concentration of short-chain fatty acids (SCFAs). This, in turn, can contribute to the progression of type 2 diabetes mellitus (T2DM) and enhance overall health [32].

3.2.3. Improvement of intestinal health. The consumption of dietary fiber is of significant importance in the prevention of constipation, alleviation of inflammatory bowel disease, regulation of body weight, and prevention of colon cancer. While the human body is unable to digest and absorb dietary fiber, intestinal bacteria have the ability to deconstruct and ferment it to varying extents, resulting in the production of a significant quantity of SCFAs. SCFA have the ability to hinder the growth of tumors through many pathways. This is the primary way in which dietary fiber helps prevent and treat colorectal cancer [8]. What's more, SCFA is the principal carbon energy source for colonocytes [1]. Meanwhile, SCFA produced by fermentation can prevent metabolic disorders, reduce intestinal permeability, decrease lipopolysaccharide translocation, and ultimately improve intestinal barrier function [7]. Research has indicated that dietary fiber, particularly soluble dietary fiber, possesses prebiotic properties that facilitate the proliferation of advantageous bacteria within the gastrointestinal tract while impeding the replication of pathogenic bacteria. Consequently, this process enhances the intestinal milieu, bolsters the host's immune response, and regulates the body's metabolic processes [33]. Dietary fiber has high WHC and SC, which can soften the stool, increase its volume, accelerate intestinal peristalsis, and promote defecation, which not only prevents constipation, but also reduces the time that carcinogens are in contact with the intestinal wall, thus reducing the incidence of colon cancer [18]. At the same time, dietary fiber can form gel in the gastrointestinal tract, which can not only adsorb cholesterol and reduce its absorption, but also exclude some potential carcinogens, such as polycyclic aromatic hydrocarbons, carcinogenic nitrosamines, etc [34]. This gel is resistant to the mechanical stresses exerted by the stomach and can maintain its physical form in gastric acid [7], and the prolonged retention of food in the stomach elicits activation of the traction receptors located in the stomach wall. This activation subsequently transmits satiety signals to the brain, leading to a sensation of satiety and a diminished inclination to consume further food [34], reducing total food intake and thus controlling body weight to prevent obesity. Within the colon, certain fermentable fibers have the capacity to facilitate the proliferation of advantageous bacteria, such as Lactobacillus and Bifidobacterium [35], while concurrently impeding the replication of detrimental bacteria, which balances gut flora. The development of colon cancer is mainly related to the prolonged residence time of carcinogens in the intestinal tract and prolonged contact with the intestinal wall [36]. Dietary fiber reduces the duration of contact between carcinogens and the intestinal wall, thus reducing the incidence of colon cancer [18]. A lack of dietary fiber in the intestinal flora can increase susceptibility to disease due to a decrease in protective mucus [37].

4. Dietary fiber extraction

The significance of dietary fiber has led to the emergence of a substantial and promising market for foods and components that are rich in fiber. Various methods, including chemical, mechanical, thermal, enzymatic, etc., have been used to extract dietary fiber in recent years. Different extraction techniques have their own advantages and disadvantages, and the dietary fiber produced by different extraction methods will have differences in molecular structure and functional properties.

4.1. Chemical method

The acid and alkaline procedures are the generally employed techniques for chemically extracting dietary fiber. However, using either approach alone necessitates a high concentration of solution, a longer duration, and results in low purity and color of the extracted dietary fiber [6], and a low cost. But the chemical reagents used in the extraction process are generally strong acids and bases, and the

DOI: 10.54254/2753-8818/57/20241255

processing temperature is extremely high, resulting in serious corrosion of the containers, pipelines, and material pumps required for extraction. A large number of anions and cations are brought into the experiments, which results in a low content of dietary fiber extracted and poor quality [8]. The main acid reagents used in the current study were citric acid and hydrochloric acid, while the main alkali reagents were sodium hydroxide and sodium carbonate [6]. The addition of hydrogen peroxide during extraction [38]. This facilitates the dissociation of the intimately interconnected components of DF and non-DF, thereby revealing the internal hydroxyl chains and consequently enhancing the water retention ability of DF [6].

4.2. *Physical method*

The primary physical technologies involved are microwave, ultrasonic, ultra-micro pulverization, extrusion cooking, high-pressure homogenization, and subcritical water extraction. Because the microwave method is not suitable for large-scale production in factories, and the ultrasonic method destroys the cell wall of the plant to be extracted to make the solvent easier to enter, both methods are more suitable as an auxiliary method [39]. There are two general types of ultra-micro pulverization methods: one is dry ultra-micro pulverization and the other is wet ultra-micro pulverization. Extrusion cooking is a continuous process combining high shear, high temperature, and high pressure and can also modify dietary fiber [6]. PVarious physical approaches have the capability to modify the microcrystalline structure of IDF, thereby augmenting the surface area of particles. Consequently, these methods can induce alterations in the processing functional properties of IDF, including its hydration capacity. Consequently, these modifications have an impact on the physiological and functional properties of IDF. They also have the advantages of relatively simple operation and environmental protection, but compared with other methods, their equipment cost is relatively high, and there are still some limitations in industrial production [40].

4.3. *Biological method*

The fundamental biological approaches encompass enzymatic and fermentation techniques. The enzymatic method is the use of specific enzymes for the specific degradation of non-dietary fiber components, such as α-amylase, which can degrade starch, protease, which can degrade proteins, etc. The advantages of the enzyme approach include its great efficiency and lack of contamination, but there are also the disadvantages of poor controllability [8]. Enzymes have the advantages of specialization and specificity; usually, the use of the composite enzyme method will result in a higher DF extraction rate and purity of extraction than the single enzyme [6]. Fermentation is the use of microbial output of proteases and amylases to degrade the non-dietary fiber components of the material, which allows for the extraction of DF [6]. The commonly used fermentation microorganisms include Aspergillus Niger, cellulase, Lactobacillus, Lactobacillus bulgaricus, green wood mould, Streptococcus thermophilus, and others.

4.4. *Combined extraction method*

The combined extraction method refers to the extraction of dietary fiber obtained by combining two or more of the above extraction methods, such as the enzyme and chemical combination method, the ultrasound-assisted method, the microwave-assisted method, etc., which can combine the advantages of multiple methods, improve the deficiencies of using a single method, enhance the beneficial characteristics of dietary fiber [40]. Since both physical and enzymatic methods have the advantages of higher extraction rates, relatively simple production operations, good properties of the IDF obtained, and environmental friendliness, combining these two methods not only combines the advantages of the two methods but also reduces the costs associated with a single method and has a better application prospect [40]. Peng et al. demonstrated that the combined microwave and enzyme treatment could release higher levels of phenolic acids compared with the treatment alone, and the obtained grapefruit peel IDF showed stronger antioxidant activity [41]. Therefore, the combined extraction method is

DOI: 10.54254/2753-8818/57/20241255

relatively simple to operate, reduces cost, saves energy, and produces high yields and high-quality dietary fiber [40].

5. Conclusion

Dietary fiber, due to its own physical and chemical properties, is effective in controlling blood glucose, blood pressure, reducing appetite and body weight, and also reduces the level of serum cholesterol absorbed by the body. Moreover, dietary fiber has been found to be highly efficacious in the prevention and alleviation of types 2 diabetes, rectal cancer, inflammation, and constipation among patients. While the human body is unable to digest and absorb dietary fiber, it can undergo fermentation by specific intestinal microbiota in the large intestine. The primary outcome of this fermentation process is the production of short-chain fatty acids (SCFA). SCFA serves various functions such as supplying energy to human intestinal cells, regulating energy metabolism, glycolipid metabolism, and intestinal flora. Additionally, SCFA aids in maintaining intestinal barriers and health, as well as enhancing intestinal immunity. In addition to protecting the digestive system's ability to function, the breakdown of dietary fiber in the colon encourages the growth of good bacteria and suppresses the growth of harmful bacteria. High-quality dietary fiber has been continuously extracted from vegetables, fruits and legumes using enzymatic, fermentation and ultrasound-assisted processing.

Dietary fiber, as one of the seven essential nutrients for human health, has an important research value and a wide range of application prospects. People can continue to explore and study the high diary fiber-rich grains in nature, their extraction and modification, and at the same time, people can develop new extraction processes or continuously optimize the extraction and processing methods of dietary fiber, and apply it more to food processing and functional foods. Subsequent studies can also continue to delve deeper into the study of dietary fiber in the gastric and large intestinal environments, as well as the role it plays in the small intestine.

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