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Review Article

Classification and regulatory perspectives of dietary fiber

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ABSTRACT

This review discusses the history and evolution of the state of dietary fiber (DF) with account of refinements in extraction methods and legal definitions subsequent to the launch of DF hypothesis. For a long time, defining and regulating DFs relied heavily on their chemical compositions and analytical methods. Although chemical compositions and analytical methods still play an important role in the definition of DF, physiological activity has also been taken into consideration. The precise definition of DF is still evolving, particularly whether oligosaccharides degrees of polymerization (DP) 3–9 should be considered as DF or not. Decades of scientific research have initiated the expansion of the term DF to include indigestible oligosaccharides with their DP between 3 and 9; hence responding to the positive health benefits of DF as well as fulfilling the needs in food labeling regulations.

1. Introduction

From crude fiber to dietary fiber (DF), DF has been recognized as resistant polysaccharides having degree of polymerization (DP) > 10 in many countries for a long time. Analytical methods, physiological effects, food regulation at national level, and other interconnected factors have been considered as important criteria in the evolution of the DF's definition in the past few decades. Some debates regarding the definition of DF still exist. Facing the dilemma of whether or not saccharide with a lower DP could be named as DF, "oligosaccharide" has been categorized as DF in food labeling systems in some countries. In the present review, various classifications of DF, physiological efficacies of DF, and evolution of definitions and measurement methods are discussed.

2. From roughage to dietary fiber

Hippocrates once said that "wholemeal bread makes larger feces than refined bread." This enlightened the importance of fiber in terms of its physiological benefits such as alleviation of constipation. In the early days, the concept of fiber was an indigestible moiety which was quantified and named as "crude

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fiber". It was referred to as the residue of plant-based food left after extraction with solvent, dilute acid, and dilute alkali [1]. It was not until 1953, the new term "dietary fiber" was introduced by the British physician Eban Hipsley. Hipsley defined DF as a sum of indigestible constituents that made up the plant cell wall, encompassing the "unavailable carbohydrate" as described much earlier by McCance and Lawrence [2] in 1929.

As suggested by Trowell [3] in 1972, DF consists of the remnants of edible plant cells, polysaccharides, lignin, and associated substances resistant to digestion by the alimentary enzymes of humans. In more detail, the constituents of DF include cellulose, hemicelluloses, lignin, gums, mucilage, oligosaccharides, pectin, and other associated minor substances (e.g., waxes, cutin, suberin). From then on, the term crude fiber was replaced by DF gradually. The compositional profile of different indigestible carbohydrates including crude fiber, nonstarch polysaccharide (NSP), soluble dietary fiber (SDF), insoluble dietary fiber (IDF), indigestible fraction, and resistant starch (RS) are summarized in Table 1.

3. Classification

DF can be classified in many different ways such as structure and solubility. In terms of structure, polysaccharides are categorized into linear or nonlinear molecules. On the basis of solubility, they can be divided into soluble or insoluble DFs. IDF consists mainly of cell wall components (e.g., cellulose, lignin, hemicellulose), while SDF consists of noncellulosic polysaccharides (e.g., pectin, gums, mucilage) [4].

3.1. *Does starch count as dietary fiber?*

Unlike Trowell's definition of DF, NSPs are carbohydrate fractions excluding starch and free sugars [5]. According to the findings from Englyst et al [6] (1992), starch can be typically divided into three fractions based on its digestive rate, including rapidly digesting starch, slowly digesting starch, and RS. RS is an extremely broad and diverse term which covers a wide range of materials, and is divided into four types, i.e., physical inaccessible starch (RS1), ungelatinized starch granules (RS2), retrograded starch (RS3), and chemically modified starch (RS4) [7,8].

In the 1980s, RS was proposed and categorized as a kind of insoluble fiber as it could not be digested in the small intestine. According to Trowell or other definitions as mentioned above, RS has been regarded as a type of DF in terms of structure and digestibility in the intestine. RS is one of the good substrates for the growth of colonic microbiota and is able to increase bacterial mass in feces [9]. Consumption of RS may stimulate the growth of specific bacteria purported to provide beneficial health effects [10]. During its fermentation, some physiologically important metabolites including short-chain fatty acids (e.g., mainly acetic, propionic, and butyric acids) are formed. Butyric acid is the most important energy source for the colonocyte cell [11]. The beneficial effects of RS on the gastrointestinal tract have also helped it gain recognition as a member of DF in some studies as well as the international food standard setting bodies such as the Codex Alimentarius Commission (Codex), European Food Safety Authority (EFSA). Codex has given a more specific explanation regarding the classification of RS. If RS is naturally present in food, it could be classified as DF. However, if it is derived from an artificial synthesis, such as physical, enzymatic, or chemical synthesis, it should provide desirable physiological benefits to be considered as DF [12–14].

3.2. *Are short-chain carbohydrates regarded as dietary fiber?*

Indigestible carbohydrates with degrees of polymerization (DP) between 3 and 9 were in general regarded as

Table 1 – Compositional profile of selected indigestible carbohydrates among different analytical methods [46–53].

Indigestible carbohydrates	Polysaccharides (DP > 9)				Noncarbohydrate residues [a]		Oligosaccharides (DP 3–9)
	Starch	Cellulose	Hemicellulose	Pectin	Lignin	Others	
Crude fiber		•	•		•	•	
Nonstarch polysaccharide [b]		•	•	•			
Soluble dietary fiber [c]			•	•		•	• [d]
Insoluble dietary fiber [e]	•	•	•	• [f]	•	•	
Indigestible fraction [g]	•	•	•	•	•	•	
Resistant starch [h]	•						

AOAC = Association Official Analytical Chemists; DF = dietary fiber; DP = degree of polymerization; NSP = nonstarch polysaccharide.

[a] Noncarbohydrate residues such as polyphenols (e.g., condensed tannin), wax, saponin, cutin, phytate, crude protein, or ash.

[b] Referring to the Englyst NSP methods, in which the be determined by gas chromatography, or by high performance liquid chromatography to obtain values for the constituent monosaccharides to determine the residual NSP after the removal of starch.

[c] Referring to the analytical method of AOAC 991.43, with which small amounts of oligosaccharides (DP 3–9) are included.

[d] Small quantities of oligosaccharides such as inulin, polydextrose, resistant maltodextrin, and short chain polysaccharides may be included in the soluble fraction. Determination of total amount of individual oligosaccharides should refer to the methods of AOAC 997.08 and AOAC 2001.03 for inulin and resistant maltodextrin, respectively.

[e] Referring to the analytical method of AOAC 991.43.

[f] A portion of pectic substances is water insoluble and is therefore included in the total amount of insoluble dietary fiber.

[g] As described by Saura-Calixto et al [53] (2000), samples were successively incubated with pepsin and α-amylase at 37°C, centrifuged, and dialyzed. The indigestible fractions consists of DF, resistant starch, resistant protein, and other associated compounds.

[h] Referring to the analytical method AOAC 2002.02.

oligosaccharides in the past. In Association Official Analytical Chemists (AOAC) official method 985.29 for DF analysis, resistant carbohydrates with DP 3–9 mostly cannot be precipitated by alcohol. As the measurement done by this method thereby only includes resistant carbohydrates with DP > 9, a debate for the proper definition of DF in association with its compositional profile is continuing. Some researches in recent years have reported that the resistant carbohydrates with DP ranging from 3 to 9 also exhibit different desirable physiological activities as most DFs does. These physiological activities might include increased stool volume, better colonic fermentation, accelerated colonic transit, and reduced levels of blood cholesterol, postprandial blood glucose, and insulin. Taking inulin as an example, this water-soluble carbohydrate has 2–60 fructose units and can be in the form of different oligosaccharides or polysaccharides [15]. Inulin is fermented at the end of the small intestine and in the colon where short-chain fatty acids are produced. These short-chain fatty acids are able to assist the growth of some probiotics such as *Bifidobacteria*, thus enhancing colon health [16,17]. As short-chain carbohydrates (DP 3–9) possess similar physiological activities as DFs, in 2009 the Codex has published a new definition of DF with short chain carbohydrates (DP 3–9) being included.

4. A comparison of physiological effects: soluble versus insoluble

Owing to the widespread publicity among the media, it has now been widely accepted that DF is a necessary component of a healthy diet and is required for normal peristalsis and constipation relief [18,19]. DFs have been revealed to aid in water retention in the colon, resulting in stools that are less dry and easier to emanate. Many studies have pointed out that both SDF and IDF have the ability to improve the gastrointestinal tract of humans in different manners. But between soluble and insoluble DFs, which one is better?

Three major mechanisms are believed to be responsible for the benefits of DF, including bulking, viscosity, and fermentation. Some fibers (generally IDF) provide bulking effect, hence increasing stool mass, alleviating constipation, and improving regularity. The increased stool weight is due to the physical presence of DF as well as the water held inside the fiber matrix. Although IDF's components, such as cellulose and lignin, are mostly not fermentable in the colon, they can effectively increase fecal bulk by their particle formation and water-holding capacity. IDFs are also associated with decrease in intestinal transit time that help prevent and relieve constipation [20]. However, SDFs which are readily fermented may increase stool bulk by promoting the growth of intestinal and fecal microflora and their by-products (e.g., gas and short-chain fatty acids, SCFAs) [21,22]. These properties might help normalize stool form through softening hard stool in constipation and firming loose or liquid stool in diarrhea [17].

Viscous fibers thicken the contents in the intestinal lumen and slow down the migration of nutrients to the intestinal walls. As a result, they can reduce the absorption of cholesterol, sugar, and other nutrients (e.g., vitamins and minerals). In addition to the fiber's viscosity, its abilty to disturb the bile salt reabsorption from the small intestine is another factor leading to the reduction of cholesterol levels. Lowering of glycemic response could further assist the reduction in insulin stimulation of hepatic cholesterol synthesis [23]. Some studies have mentioned that the consumption of IDF slightly affected dietary mineral absorption, but nondigestible oligosaccharides have been reported to stimulate intestinal microflora to produce vitamins and SCFA which might promote mineral absorption [24,25].

Fermentable fibers are fermented in the colon and promote the growth of beneficial bacteria in the intestine. The colonic microflora can ferment certain types of DFs and produce short chain fatty acids, which help maintain the integrity of colonic cells and trigger a cascade of additional beneficial effects. SDF is readily fermented and causes some remarkable changes in the colon. It could build up important microflora by acting as a substrate food for beneficial microorganisms, and consequently improve host health [26].

From a functional perspective, not all fibers have the same effects; it depends on the dosage and types of fibers. For instance, indigestible carbohydrate (e.g., fructo-oligosaccharides) having desirable physiological activities in the gut can help alleviate constipation symptoms with a lower dose (approx. 10 g/d), although other fibers (e.g., polydextrose, RS) do not show any apparent effects on relieving constipation symptoms at doses up to 50 g/d [27,28]. Some previous studies have reported that stool moisture content might remain at 70–75% regardless of the amount of fiber and water consumed [29]. In the worst case scenarios such as inadequate water intake, symptoms of chronic constipation of some patients might get worse if DF intake was increased [30]. Another study has found that lactulose was more effective in easing constipation when compared with other indigestible carbohydrates [31]. Depending on the size, composition, and physiochemical properties, the physiological activities of different DFs can be varied. No single DF is able to provide full scope of physiological functions. Therefore, it is suggested to choose a variety of fiber-rich foods or fiber sources in the daily diet in order to obtain a wider range of physiological functions from DFs.

5. National regulations and definitions

The concept of DF was introduced in the latter half of the past century. In 2009, a new definition of DF was published by Codex, along with its corresponding official analytical methods, reference nutrient levels, health claims, and standards. In fact, giving a universally accepted definition to DF has still been both challenging and controversial for several reasons: (1) DF can neither be defined as a single chemical entity nor a group of related compounds; and (2) different fiber types may have similar or overlapping health benefits, making it difficult to define them solely by health outcomes. Many countries and international institutions reconsider whether the original definition of DF needs to be revised.

According to different national regulations, the definition of DF varies from country to country. For instance, the United Kingdom defines DF based on the chemical properties and digestibility whereas the United States considers substances that can be fermented in colon. France's definition is the closest to that established by Codex, in which composition and polymerization of carbohydrates are considered along with their physiological properties [14,32].

DFs do not solely refer to indigestible carbohydrates. DF analyses using different methods can produce distinct results in its compositions and chemical entities. Table 1 shows the compositions of some selected indigestible carbohydrates obtained from different analytical methods. The saccharide compositions are subjected to be dissimilar among the six indigestible carbohydrate moieties. Many scientists including Southgate [33] (1977), Theander and Aman [34] (1979), Schweizer and Wursch [35] (1979), Furda [36] (1981), Heckman and Lane [37] (1981), Baker [38] (1981) and Asp et al [39] (1983) have contributed their efforts to the evolution of “dietary fiber”. Their goal was to develop analytical methods to quantify DF based on the definition as described by Trowell. By 1985, Leon Prosky has accomplished a collaborative effort and successfully reached consensus within the scientific community on DF quantification. The findings in their collaborative works later received acceptance as being the reference methods for DF analysis, including AOAC 985.29 (AOAC Official Method 985.29) and AOAC 991.43 (AOAC Official Method 991.43). However, these official methods are not suitable for the measurement of short-chain carbohydrates with DP 3–9. Oligosaccharides, such as fructo-oligosaccharides, galacto-oligosaccharides, and polydextrose, thus cannot be quantified using these methods. If oligosaccharides (DP 3–9) are present in the samples to be analyzed by the above AOAC methods, other analytical approaches may be necessary to measure the total amount of indigestible carbohydrates with DP $\geq$ 3 [40].

The most recent official DF measurement method, AOAC 2009.01, has applied pancreatic α-amylase treatment at physiological temperature (e.g., 37°C) to better mimic human digestion condition [41]. This method is different from all other enzymatic gravimetric methods (e.g., AOAC 985.29), which use heat-stable α-amylase with a digestion temperature of ~100°C. In the AOAC 2009.01 method, samples are incubated with pancreatic α-amylase and amyloglucosidase simultaneously under near-physiological conditions (37°C, pH 6). Subsequently, the mixture is incubated with protease to hydrolyze the bulk of protein to peptides, preventing it from being precipitated later in the alcohol precipitation step. After DF of high molecular weight (i.e., DP > 9) is precipitated, the supernatant is further analyzed with high performance liquid chromatography to measure the amount of DF with low molecular weight (i.e., DP 3–9). The total SDF content is calculated as the sum of high and low molecular weight DFs. It is worth noting that the enzymes used in this method are sufficiently pure to give no hydrolysis and loss of nondigestible oligosaccharides such as, fructo-oligosaccharides, galacto-oligosaccharides, xylosaccharides, resistant maltodextrins (e.g., Fibersol 2), or polydextrose [42].

While DF is redefined by Codex, many official institutions such as the Food and Drug Administration of the United States, EFSA, China Food and Drug Administration, Food Standards Australia and New Zealand, and Health Canada (Table 2) have followed the path and also made some corresponding revisions on the DF definition, i.e., adding oligosaccharides (DP 3–9) to the definition. Quantitative analysis method was also updated to AOAC 2009.01 in most of the countries as mentioned in Table 2 [43,44].

Table 2 – Lists of institutions and countries accepting oligosaccharides with DP 3-9 as dietary fiber [43,44,52–54].

List of institutions	List of countries
• American Association of Cereal Chemists (AACC)	• Brazil
• Association Official Analytical Chemists (AOAC)	• Canada
• Codex Alimentarius Commission (CAC)	• Chile[a]
• European Food Safety Authority (EFSA)	• China
• Food and Drug Administration (FDA)	• Indonesia
• Food Standards Australia and New Zealand (FSANZ)	• Japan
• Institute of Medicine (IOM)	• Korea
• International Life Science Institute (ILSI)	• Malaysia
	• Mexico
	• Singapore
	• Thailand
	• Taiwan

DF = dietary fiber; DP = degrees of polymerization.
[a] Chile separates soluble and insoluble DF in food labeling and also includes oligosaccharides (DP 3–9) as DF.

Although some countries have accepted the inclusiveness of oligosaccharides (DP 3–9) as part of DF, their official analytical method for the determination of DF for food labeling systems might not yet be renewed to AOAC 2009.01. For example, in Taiwan the definition of DF as defined by the governmental agency is an edible carbohydrate with DP $\geq$ 3 plus lignin [45]. Although oligosaccharides (DP 3–9) are included in the Taiwan Food and Drug Administration's definition of DF, the announced reference method for DF anlaysis is still AOAC 985.29. This may lead to an underestimation of DF content as well as a conflict in the food labeling system.

For a long time, the development of definition of DFs relied heavily on their chemical compositions, analytical methods, and physiological activity. The precise definition of DF is still evolving, particularly, whether or not oligosaccharides DP 3–9 should be considered as DF. Codex has modified the definition of DF by including short-chain carbohydrates with DP 3–9. The concept of adopting oligosaccharides (DP 3–9) as part of DF has been accepted by many countries and international institutions. Changes in food labeling systems are anticipated in the coming years. From a technical point of view, corresponding analytical methods particularly for oligosaccharides (DP 3–9) has already been available to avoid underestimation of DF content and also to fulfill the needs in food labeling requirements.

Conflicts of interest

All contributing authors declare no conflicts of interest.

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