

# Recommendations for characterization and reporting of dietary fibers in nutrition research

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## ABSTRACT

Dietary fiber (DF) comprises a wide range of naturally occurring and modified materials with substantial variations in physical and chemical properties and potential physiologic effects. Although nutrition studies testing the effects of DF usually provide extensive detail on the physiologic responses, many still fail to adequately report the type and properties of the DF itself. This weakens the ability to directly replicate and compare studies and to establish structure-function relations. We outline the factors that affect DF functionality and provide 4 overarching recommendations for the characterization and reporting of DF preparations and DF-containing foods in nutrition research. These relate to 1) undertaking characterization methods that reflect the study hypothesis; 2) adequate reporting of DF source, quantity, and composition; 3) measurement of DF rheological properties; and 4) estimation of the DF fermentation rate and extent. Importantly, the food matrix of the test products should also be considered, because this can influence DF functionality and hence the apparent DF efficacy for health-relevant outcomes. Finally, we point out differences in DF functionality to be considered in acute and longer-term trials, the need to design the control treatment according to the research question, and the importance of reporting the amount and type of DF in the background diet. *Am J Clin Nutr* 2018;108:437–444.

**Keywords:** gelling, viscosity, fermentability, molecular weight, dietary fiber properties, food matrix

## INTRODUCTION

Dietary fiber (DF) is a nutritional concept comprising an array of plant-derived or eventually other carbohydrate oligomers and polymers not hydrolyzed by endogenous enzymes in the small intestine of humans (1). The molecular and physical characteristics vary widely, even within a given source or type of DF (e.g., guar gum, pectin), depending on the specific source, degree and method of isolation, and food processing and matrix. Higher intakes of DF in general, and of some specific DFs, have repeatedly been associated with various benefits for health and the re-

duction in disease risk (2–4). However, it is clear that not all DFs confer the same health-related benefits, because the different specific characteristics of DF in food lead to different physiologic responses (5–7).

Structural DF features that confer particular physical properties linked to different physiologic functionalities are summarized in **Figure 1**. The type and amount of DF in a meal may cause changes in gastric emptying and intestinal transit and nutrient absorption, with consequent effects on gastrointestinal hormone responses (8). After reaching the large intestine, DF will be at least partly fermented at a rate dependent on its structure, interacting with the gastrointestinal conditions and microbiota. This results in DF-specific metabolites and affects the gut microbiota composition and activity (9).

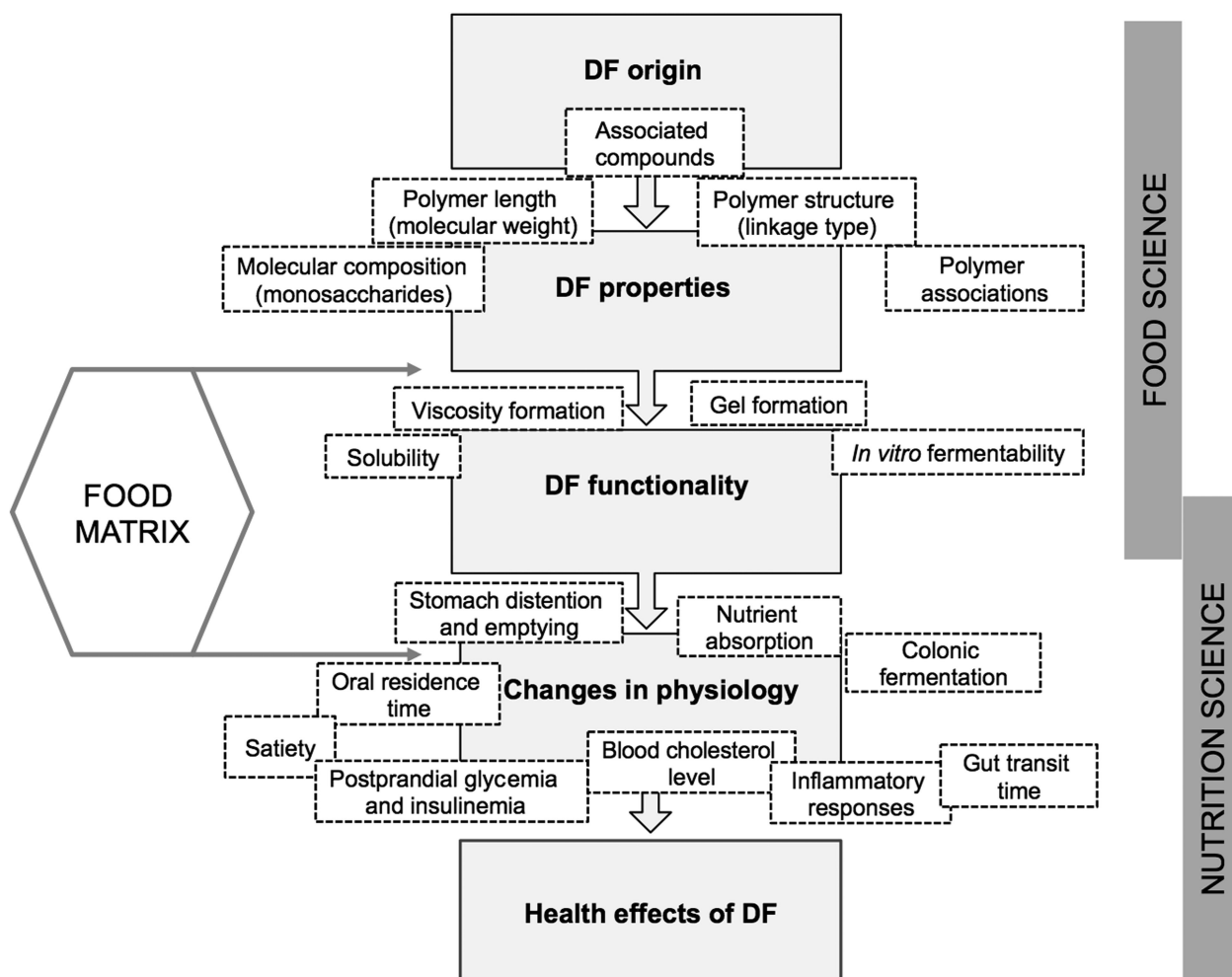
Despite awareness of the diversity of DFs and the large volume of work related to their effects on an array of physiologic and metabolic outcomes, surprisingly little attention has been paid to consistently defining and reporting the DF materials used in nutrition research. This has important implications for the translation of DF research into practice. For example, a wide range of proposed claims related to the health effects of DF have not been authorized in the European Union, due largely to inadequate

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**FIGURE 1** Properties, functionalities, and physiologic effects of DF relevant to health outcomes. DF, dietary fiber.

characterization of the materials used in the supporting research (10). This reflects the recognition that evidence for the claimed benefits of a given DF can only be reliably applied to that same DF or another sharing the same physiologically relevant properties.

Given the diversity of both DF properties and physiologic mechanisms of action, adequate specification of DF at the levels shown in Figure 1 is absolutely necessary in order to identify and replicate the exact materials used in nutrition studies. This is needed to ensure the validity of comparing and combining studies in meta-analyses, and to establish reliable, predictive, structure-function relations between specific DF or DF-containing foods and their physiologic effects. If only the DF origin or name is given, even the most detailed and advanced nutritional physiology measurements will not bring us any closer to explaining what characteristic of the DF was relevant, nor to predicting with confidence what other sources of DF might likely have the same effects. Furthermore, because an increasing amount of dietary DF comes from commercially manufactured DF-containing ingredients and products, knowledge of DF structure-function relations will also aid in developing foods and ingredients with desired health efficacy. Last, in dietary interventions, only part of the DF intake comes from the test food, making

it important to also control and report the DFs of the background diet.

The magnitude of the problem in nutrition research is shown by our recent systematic review of DF properties in relation to appetite and energy intake outcomes, in which 75% of otherwise eligible articles were excluded due to inadequate characterization of the DF (11). Furthermore, even when DF properties were reported, the approach and methods used for characterizing these also varied widely. We concluded that improved DF characterization and reporting standards are urgently needed to maximize the value of published research and to develop better mechanistic knowledge and reliable prediction of the effects of specific DFs in nutrition.

There are previous examples in the Journal of recommendations for the specification and reporting of other complex dietary components, such as flavonoids (12) and botanical supplements (13). Many of the issues identified in those recommendations also apply to DF, especially with regard to source description and analytical specifications. The objective of the present Perspective article is to suggest some basic criteria and considerations for the identification and characterization of DF and DF-containing test foods in nutrition research and standards for reporting these in the professional literature.

## RECOMMENDATIONS FOR DF CHARACTERIZATION

### **Recommendation 1: Each study should pose a clear hypothesis relating the DF properties to a putative physiologic functionality and characterize DF accordingly**

Many hypotheses in research testing the effects of DF on health-related outcomes are implicitly or explicitly underpinned by the idea that specific properties of DF act via intermediary processes that may affect physiologic variables such as mastication and oral residence time, gastrointestinal transit, nutrient availability, or gut fermentability. In many cases, the known properties or reported effects of a DF will drive hypotheses. The targeted physiologic processes should, in any case, justify the selection of the type of DF to be tested, but more importantly, also dictate the specific type of physical characterization that should be undertaken. Linking the hypothesis to the characterization can also facilitate the selection and validation of more predictive preclinical physical and *in vitro* testing methods, with the use of conditions most closely mimicking the physiologic environment in which the DF is proposed to exert its effects. Specific implications of this are elaborated in the recommendations that follow.

### **Recommendation 2: DF source, quantity, and composition in test materials should be specified sufficiently to allow for independent sourcing and replication of the research. The molecular weight or degree of polymerization of the targeted DF polymer in the test food should be given**

In all cases, the DF material studied needs to be unambiguously chemically specified and quantified. This applies both to the DF under investigation and (if different) to the inherent DF of the food matrix vehicle, and of the control and in the background diet. The analytical specification of extracted, isolated, or chemically synthesized materials is particularly crucial. Under the Codex Alimentarius definition of fiber (14), which has been widely incorporated into regional and national guidance, these materials (unlike the DF inherently present in foods) can only fulfill the definition if they have been shown to show a beneficial physiologic effect. Unambiguous specification of these materials, especially if new or novel, is therefore essential to substantiation and authentication of their status as DF (as well as for any potential health claims). Most DF preparations are not 100% DF but also contain other constituents. Thus, data on the amount of DF used in the test foods should always be based on analytical data from a specified method. If suitable food chemistry collaboration is not available, there are numerous service laboratories available for such analyses.

In the time since the establishment of the DF concept, a range of definitions and quantification and analysis methods have been developed and debated. Standard methods have been adopted for labeling purposes, mostly based on digestion with alimentary enzymes and quantification of the resistant polymers. The standard DF analysis methods also provide for the quantification of “insoluble” and “soluble” DFs, which is a very crude way of estimating potential functionality. Earlier methods that did not capture certain nondigestible oligosaccharides have been amended, so these compounds are now generally included in the total DF quantification (15). It is important to recognize that DF definitions (and analytical procedures) for labeling

purposes are not fully globally harmonized (16). When DF quantification of the background diet is based on labeling information or nutrition databases, these should be clearly stated and described.

When DF is administered as part of a meal or diet, the DF of these should be quantified and specified as well, because the overall food composition, matrix, and processing steps may influence the characteristics of both inherent and added DFs. When using DF preparations extracted from plant materials, or when using foods containing inherent DF (e.g., cereals, pulses, fruit), the DF content of the ingredients and test foods used should be reported, along with the source and also preferably the method used to obtain these values. In the case of DFs inherently present in test foods, it also would be useful to refer to the diversity of DF types present. It should also be noted that, in addition to carbohydrate moiety, DF sources can also comprise bioactive phenolic constituents (17, 18) and their quantification is recommended, particularly in the case of berry and fruit DF and some other inherent DF sources, and especially when long-term effects are studied. As the science develops, the health relevance of other chemical properties or associated constituents of DF sources may be hypothesized, which further justifies the value of a thorough analysis and reporting of test materials.

In addition to providing exact quantification, when specific DF ingredients are used, other details should also be given. For example, the degree of methylation of pectin (19), the degree of purification of  $\beta$ -glucan (20), and the ratio of mannuronic and guluronic acid in alginate (21, 22). This is because the physical properties of DF and thus physiologic outcomes are highly dependent on the molecular structure of the specific materials used. It is particularly important that the molecular weight (MW) or degree of polymerization of the DF is reported. In the case of inherent DF sources with many components, the MW of the component or components or the MW and distribution of hydrolyzed materials contributing to the hypothesized effects should be given. These inherent chemical properties of the DF itself are important for the many potential functionalities expressed at the level of the food or ingesta, such as viscosity and fermentability as discussed below, and for the assignment of causal structure-function relations. Food chemistry and technology studies have shown substantial variation in DF polymer MW due to raw material origin or food processing (23–25). MW is typically analyzed by gel permeation chromatography with generic (refractive index, light scattering) or specific (staining) detection methods (26, 27). Because such methods are not often available in nutritional research groups, the information should be obtained from the DF supplier or collaborations with food chemists and analysts should be sought to make such analyses available.

### **Recommendation 3: When the hypothesized mechanisms of action of DF are related to development of viscosity or to gel formation, these properties should be measured in the matrix and conditions most relevant to the hypothesis**

The binding of water to develop viscosity or to form gels is an important physical effect of DF on foods or the digesta. Unlike MW and chemical composition, which are inherent to the DF itself, viscosity and gel-forming are manifested as properties of the DF-containing matrix and milieu. The effects may be observed in the product as consumed (influencing mastication and mouthfeel)

or may develop or change as the ingested materials are exposed to the gastrointestinal environment. Viscosity and gelling should be accordingly measured in relevant conditions.

Proper dispersion and hydration are prerequisites to fully realize the potential viscosity and gel-forming capacity of a DF source. The capacity to achieve these depends on the concentration of DF and a number of other factors, such as hydration time, pH, temperature, mixing conditions (shear rate), presence of certain cations, presence of soluble solids, and the presence of and synergy with other hydrocolloids. The food matrix in which the DF is incorporated is also very relevant. First, the composition of the food could affect the DF physical properties (e.g., the presence of sugar decreases viscosity). Furthermore, the manufacturing process (e.g., baking, cooking, extrusion, and high hydrostatic pressure) of the food often modifies the DF polymer interactions, composition, and especially MW (5, 23, 24, 28), which, in turn, leads to changes in its functional properties.

Viscosity and gel characteristics can be measured either from a water (or simulated gastric fluid) dispersion of the DF itself or from a dispersion of the food matrix incorporating the DF. Although it is critical to know exactly what DF materials are present in test foods, physical data on the DF by itself only address part of the question. Viscosity depends on the liquid fraction and the concentration, shape, size, and buoyancy of the food particulates (29). This means that it is important to report the pretreatment steps, such as comminution, dilution, sieving, centrifugation, etc., used to obtain *in vitro* food digesta. Shifting from the simplistic approach to a more integrated food-based approach is recommended, because the physiologic effects are mediated by the DF-containing foods and not by DF in isolation. These steps are not only relevant to ensuring adequate sample preparation for physical measurements but the use of physiologically realistic pretreatments can also establish whether a DF source as consumed is likely to be fully dispersed and hydrated *in vivo*. For DF consumed in liquids this is generally less of an issue, but for DF in denser or solid food formats or capsules there is considerable uncertainty whether complete dispersion and hydration are actually achieved. Failure to consider this may lead to a significant overestimation of the physical effects in the body. The use of *in vitro* dissolution tests (commonly used in the pharmaceutical industry) or dynamic gastric models (30, 31) is recommended when there is any doubt about this. The measurement conditions also need to be considered and should be hypothesized. If the effects of DF are hypothesized to occur in the stomach or small intestinal phase, the pH, mixing, and enzymatic conditions should be adjusted accordingly, and at physiologic temperature.

Viscosity is defined as the resistance to flow. The capacity of DF to produce viscous solutions upon dissolution in water depends on its MW and concentration (32). The occurrence, composition, and distribution of branches on the polymer backbone also influence polymer viscosity properties because branched polymers with the same MW as linear polymers have different hydrodynamic volumes (7). This chemical heterogeneity of DF as well as the food matrix make it difficult to elucidate which exact conditions are important for viscosity development for a given DF and food format.

Most viscous DF solutions exhibit non-Newtonian, pseudoplastic flow, also known as shear-thinning, because their

apparent viscosity values decrease when the shear rate increases. Due to this dependence on shear rate, measurements to characterize the flow behavior of DF solution should be made at a range of shear rates to obtain complete flow profiles (33). Current instrumentation allows fitting the viscosity values (across the shear rate interval selected) to different mathematical models. For most fluids, a “power law” equation applies and we recommend obtaining the complete flow curve over a wide shear rate interval and reporting the equation parameters ( $K$  and  $n$ ) because this will allow the calculation of apparent viscosity at any single shear rate value of interest. In addition, for easier comparison with other research, it is helpful to note the apparent viscosity at shear rates such as 10 or 50/s, which have commonly been reported in the literature to reflect *in-body* conditions (11). However, there is no consensus on the actual shear rate most relevant to the stomach digestion phase because peristaltic movement produces mechanical forces that are difficult to simulate exactly as they occur *in vivo* (34). The reporting of viscosity at other shear rates may also be justified by the hypothesized site of action. Examples of reference methodologies for measuring viscosity are given in **Table 1**.

Gels have been characterized as “a rigid structure that is resistant to flow . . . exhibiting both characteristics of a liquid and a solid” by Saha and Bhattacharya (50) in their overview of food gels and the main gel-forming DFs. Many DFs form gels under appropriate conditions, and this may affect the sensing, transit, and digestion of foods and nutrients in the gastrointestinal tract. These can range from weak gels (exhibiting more elastic than viscous behavior) to self-standing rigid structures. (See **Table 1** for examples of reference methodologies for characterizing gels.)

In many cases, the gelling of a DF is initiated or strengthened by the presence of specific mineral cations, low pH, or temperature conditions. These have been exploited to propose uses in foods and beverages in which the gelling mainly occurs only under *in-body*, postingestive (e.g., gastric) conditions (51, 52). This has the benefit of reducing possible adverse effects of the DF on processing and texture and mouthfeel during consumption. As noted above, when such effects are hypothesized or likely to contribute to putative physiologic effects it is essential to assess gel characteristics in the relevant chemical and environmental conditions.

Characteristics reflecting the strength of gels can be determined by different measures, particularly the force to fracture (51). An example of how this can be used in establishing structure-function relations is described by Ström et al. (36) and Peters et al. (52) for high-guluronate alginates and satiety. In these studies, liquid alginate-containing products containing a source of soluble calcium were acidified and allowed to set in molds. The resulting gels were removed and hardness (force to fracture in compression) was measured by a universal testing machine or texture analyzer. These data suggested a minimum gel strength for these compositions (when tested under “gastric” conditions), which would be a likely prerequisite for having a meaningful satiety effect in practice. The formation of these gels under gastric conditions *in vivo* has also been confirmed with the use of MRI (22). Similarly, Jensen et al. (21) used oscillatory shear rheology to determine the elastic modulus of acid gels from alginates with differing mannuronic-to-guluronic acid ratios. These are

**TABLE 1**Recommendations for characterization of DF in nutritional research<sup>1</sup>

| Recommendation                                                                                                                                                                                                                         | Rationale                                                                                                                                                                                                                                                                                    | Points to consider                                                                                                                                                                                                                                                                                                                                                  | Example methodology and suggested reading (references)                                                                                                                                                   |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1. Each study should pose a clear hypothesis relating the DF properties and putative physiologic functionality and characterize DF accordingly.                                                                                        | What are the putative mechanisms behind the hypothesized DF-related physiologic benefits<br>Use the hypothesis as a basis for choosing what DF properties need to be defined                                                                                                                 | In which part of the digestive tract is DF expected to exert its effects?<br>How large an effect of DF properties (e.g., change in MW, viscosity, or fermentability) is likely needed to have a meaningful physiologic impact?<br>Define also the in vivo trial (time frame, control products, etc.) based on the hypothesized mechanism                            | (19, 35, 36)                                                                                                                                                                                             |
| 2. DF source, quantity, and composition in test materials must be specified sufficiently to allow for independent sourcing and replication of the research. The MW and/or DP of the major DF polymer in the test food should be given. | Development of new DF preparations with physiologic benefits relies on nutrition research giving adequate specification and data about DF properties<br>Health claim substantiation, validity, and enforcement require that the DF sources used in clinical research are precisely described | The same general type of DF but with a different specification or in a differently processed food or another food matrix can have markedly different physiologic effects<br>Adequate analysis methods, if not available in the study group, should be sought from DF producers, commercial analysis laboratories, or by collaboration with suitable food scientists | Details of sourcing, generic or chemical names, structure, MW, preparation (24, 26, 37–39)<br>Quantification by analysis (15) or label or database sources                                               |
| 3. When the hypothesized mechanisms of action of DF are related to development of viscosity or to gel formation, these properties should be measured in the matrix of use and conditions relevant to the hypothesis.                   | Characteristics of (isolated) DF sources differ depending on the food or beverage matrix in which they appear; the ingested material will be exposed to differing environments in the body, which can markedly alter the properties from pre-ingestion (“product”) conditions                | Where and when in the digestive tract is DF expected to function?<br>What conditions (temperature, pH, shear, enzymes) are encountered up to and at that point?<br>What is the nature of the ingested material and conditions there?<br>In vitro measurements on DF should be done under the relevant (hypothesis-led) simulated gastric and duodenal conditions    | Flow characterization over a range of shear strains (32, 33, 40, 41)<br>Gel strength measurement (21, 36, 42, 43)<br>Mastication and dynamic gastric models (30, 31, 44)<br>Dissolution testing (30, 45) |
| 4. When gut-mediated mechanisms are considered, DF fermentation rate and extent should be measured in vitro.                                                                                                                           | Molecular structure, DP, and potential cell wall matrix integrity define the accessibility of DF as substrate for the gut bacteria                                                                                                                                                           | Rate and extent of simulated gut fermentation and types of end products (gases and short-chain fatty acids)                                                                                                                                                                                                                                                         | In vitro fermentation methods using fecal microbiota in anaerobic conditions (46–49)                                                                                                                     |

<sup>1</sup>DF, dietary fiber; DP, degree of polymerization; MW, molecular weight.

examples of a more general approach to develop structure-function relations that can be used for other DFs, food formats, and health-related outcomes to generate mechanical testing criteria for selecting and optimizing formulations for use in clinical efficacy testing. Although this has initially been applied (and is probably easiest) to DFs added to liquid matrices, there may be wider potential applications for more common DF-containing semisolid and solid foods, such as grain-based products. This may also be used to ensure that DF functionality is retained after different types of processing.

**Recommendation 4: When fermentation-mediated mechanisms are hypothesized, DF fermentation rate and extent should be established in vitro and confirmation of this sought in vivo**

All DFs, also those considered to primarily influence physiology by their effects on digesta rheology, will enter the large intestine and will be at least partially metabolized by the diverse colonic microflora (7, 53). The rate and extent of the fermentation vary and are influenced both by the solubility and chemical composition and structure of the DF, as well as the host microflora

composition. In addition, DF inherently bound to plant cell walls, such as that in wheat bran, or very insoluble DF such as cellulose, are slowly fermentable. On the other hand, soluble poly- and oligomers, such as  $\beta$ -glucan and fructo-oligosaccharides, are rapidly fermentable (54, 55).

Many human studies of DF have used analyses of hydrogen in breath or short-chain fatty acids in blood or stools as indicators of DF fermentability. These can be seen as confirmatory physiologic measures under specific clinical test conditions, rather than a method of DF characterization. An established method for characterizing the fermentability of DF is the analysis of short-chain fatty acid formation and/or the gas production rate of DF in vitro under anaerobic conditions with the use of human fecal inoculum. Interlaboratory testing to harmonize the measurement was made long ago (46), and studies to assess the effect of other DF properties on fermentation rate and end products have been reviewed (47, 48). We recommend that the fermentability should be tested in vitro with the use of these standardized methods to confirm and provide a basis for comparison of specific DFs before undertaking human clinical testing when the hypothesis includes fermentation-mediated effects of DF. Even though fermentation is influenced by the type of bacterial flora used, fermentation rate and extent of different DF preparations can be compared in vitro. Although these in vitro methodologies have limitations, they provide predictive tools about DF physiologic potential, which can be used in selecting materials for verification in vivo.

DF characteristics are also known to affect gut microbiota composition (56). Prebiotics have been defined as a particular class of DFs that are selectively fermented, resulting in specific changes in the composition and/or activity of the gastrointestinal microbiota, thus conferring a benefit or benefits on host health (57). Special methods have been suggested to evaluate the prebiotic potential of DF sources (58). On the other hand, prebiotics have also been considered as too narrow of a concept considering the multiple interactions between nondigestible carbohydrates and the gut microbiota (53). Recently, an international expert panel updated the definition of a prebiotic: "a substrate that is selectively utilized by host microorganisms conferring a health benefit" (59). This definition expands the concept to possibly include noncarbohydrate substances and applications to body sites other than the gastrointestinal tract. Especially in long-term studies, it is important to consider the link between fermentability of DF and its food sources by bacteria in vitro and its potential to affect gut signaling in vivo. In more complex DF-containing ingredients and foods, the noncarbohydrate parts of DF sources will also be metabolized and phytochemicals converted to metabolites that may also play a role in DF-associated signaling. These effects can also be predicted in vitro to estimate the potential physiologic effects of, for example, the phenolic constituents in DF sources (49, 60).

## KEY CONSIDERATIONS OF STUDY DESIGN

### Study duration

As stated above, the study design and DF analyses should be planned according to the research hypothesis. When considering acute (e.g.,  $\leq 4$ –6 h) postprandial responses, DF influences may be due to changes in oral processing or subsequent effects of the

food bolus properties in the gastrointestinal tract. Here, the rheological properties of DF clearly play a dominant role, and hence should be measured. When the follow-up time is longer, contributions of colonic fermentation can additionally be considered, and hypotheses derived from knowledge about DF fermentability become increasingly relevant. In interventions lasting several days or weeks, DF-induced changes in gut microbiota activity and/or composition and the resulting systemic changes in physiology may start to play a role. In this case, the molecular composition and ability of DF to support the growth of gut microbiota are of interest. Depending on the existing background diet of the study population and amounts of DF to be added, these data may indicate that a longer study duration would be justified. As noted, however, a potential role of non-DF components in DF-rich foods and ingredients should also be considered (60, 61).

### Control treatment

The reference or control treatment is an essential part of the study design and also determined by the specific research question. When the research question is whether a specific type or source of DF influences the physiologic outcome of interest, the control treatment should be the same diet without that DF [i.e., it is the (added) presence of that specific DF in the diet that will be tested]. The amount and type of DF in the background diet should also be reported. Unless pure extracts are used, however, such a design will always examine effects of the DF source as a whole, in most cases meaning a mixture of various DFs. When instead the research question pertains to the influence of a particular DF characteristic and related mechanism of action, various forms or levels of the physicochemical characteristic of one specific DF source may be compared with each other, and the control should then contain the same amount of DF as the test group or groups but with different characteristics. Studies of this kind include, for example, the use of pectins with varying gelling properties or  $\beta$ -glucans with variable MW. In these cases, not only the effects of the amount and presence of a particular DF can be studied but also the role of the specific DF properties and functionality on the physiologic outcome. Similarly, different DF sources with quantified variations in specific characteristics may be compared with each other.

### Study population

As in all nutrition research, a clear hypothesis-led primary outcome and adequate statistical power are relevant to ensuring a reliable effect size estimate and interpretation of results. Studies should be well controlled, particularly with regard to the target population to reduce interindividual variability in, for example, gastrointestinal transit, which, in many cases, directly influences the physiologic effects of DF (62). This includes population characteristics such as body weight, age, sex, or habitual diet, which all can influence gastrointestinal transit (63–65). The latter may also be of particular importance for experiments that study the beneficial effect of a DF via modulating the gut microbiota because individuals with differing habitual diets are likely to have distinct baseline gut microbiota compositions (56, 66) and, as a result, responsiveness of a DF to exert a physiologic effect via the gut microbiota may differ significantly. Other population

characteristics in that respect include age (67), sex (68), and antibiotic use and disease (69) and should therefore be considered or controlled for.

## CONCLUSIONS

DF by its definition is a heterogeneous concept that incorporates a number of variables in terms of possible compositions and functionalities, as depicted in Figure 1. For meaningful scientific research that allows for valid replication and comparison of studies, as well as setting DF criteria for beneficial physiologic effects and related health claims, DF ingredients and foods used in nutrition research should be fully characterized and adequately reported. At the very minimum, we believe that a clearly stated hypothesis linking putative benefits to established DF properties and unambiguous specification of the DF materials (i.e., recommendations 1 and 2 from Table 1) should be required for undertaking and publishing original research testing the physiologic and health effects of DF. The development of better raw materials, ingredients, and foods will only be possible with effective collaboration between nutrition and food sciences. To combine the approaches of these scientific fields, each typically covering only part of the continuum shown in Figure 1, there should be no “black boxes” between them. Improved characterization of the DF and food structures used in dietary interventions is clearly needed to further advance and maximize the value of nutrition research.

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At the time of this work, RES and DJM were employees of companies manufacturing fiber-containing foods or beverages or fibers as ingredients. KSP and SPP, as part of their work, contribute to research contracted by food companies. In addition, KSP is a board member of the company Leipurin, which sells ingredients to the baking industry. SF and CFMM have no conflicts of interest.

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