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Review

Beyond soluble and insoluble: A comprehensive framework for classifying dietary fibre's health effects

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ABSTRACT

Despite evolving definitions, dietary fibre classifications remain simplistic, often reduced to soluble and insoluble types. This binary system overlooks the complexity of fibre structures and their diverse health effects. Indeed, soluble fibre is not just soluble but has important qualities such as fermentability, attenuating insulin secretion, and lowering serum cholesterol. However, this limited classification fails to account for dietary fibre diversity and predict their full range of physiological effects. This article proposes a holistic classification framework that accounts for different fibre types and can be used to accurately infer their physiological outcomes. This proposed classification framework comprises of five constituents: backbone structure, water-holding-capacity, structural charge, fibre matrix and fermentation rate. This model more accurately captures the structural and functional diversity of dietary fibres, offering a refined approach to predicting their health benefits.

1. Introduction

Hippocrates espoused the relationship of diet to human health centuries earlier, purportedly stating, "Let food be thy medicine and medicine thy food" (Smith, 2004). During the mid-twentieth century the modern Western diet established itself as an effective means to feed the growing populace. The modern Western diet, characterized by high levels of refined sugar, sodium, and *trans*-fats, and low in fruits and vegetables, has been linked to gut dysbiosis and the rise of non-communicable diseases, including type 2 diabetes, obesity, and cancer. These diseases are responsible for causing more than 70 % of annually reported deaths (Ayakdaş & Ağagündüz, 2023; Birt et al., 2013; Cheng et al., 2022; Clemente-Suárez et al., 2023; Rakhra et al., 2020). A healthy diet has been shown to reduce inflammation, improve insulin sensitivity, and support endothelial function, antithrombotic factors and microbiota diversity (Devi et al., 2014; Locke et al., 2018; Rakhra et al., 2020; Schwingshackl et al., 2020).

Dietary fibre is known to alleviate constipation, lower cholesterol, reduce cancer metastasis, and improve overall mortality rates (Buttriss & Stokes, 2008; Grigor et al., 2016; Reynolds et al., 2022). Although, discussed for centuries, the term "dietary fibre" was formally introduced by Hipsley in 1953 (Cui & Roberts, 2009; Hijová et al., 2019; Hipsley, 1953). Hipsley described fibre as parts of the plant cell wall that cannot be digested. However, different disciplinary groups and organisations continually modified it until 2009, when the CODEX Alimentarius Commission defined dietary fibre as carbohydrate polymers consisting of ten or more monomeric units that can move through the small intestine without hydrolysing. Dietary fibres can be naturally present in the consumed food, derived from food materials and synthetic carbohydrates that induce health benefits. Additionally, lignin or other plant wall substances can be included, and carbohydrates between 3 and 9 monomeric units are left to national authorities to determine their suitability as a dietary fibre (Jones, 2014).

Dietary fibre is composed of a finite number of monosaccharides including (glucose, galactose, mannose, fructose, arabinose, xylose, rhamnose and fucose, linked in varying ways to form complex structures). Despite the limited types of monosaccharides, these simple sugars can form a large variety of secondary and tertiary structures,

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contributing to the great complexity of fibres (Hamaker & Tuncil, 2014). Dietary fibres include non-starch polysaccharides, resistant starches, non-digestible oligosaccharides and synthetic carbohydrates (Buttriss & Stokes, 2008; Fu et al., 2022). Their structures are summarised in Table 1. Each dietary fibre has a unique primary, secondary or tertiary structures that contributes to its physiological effects.

The current classification of dietary fibres has them grouped into soluble and insoluble fibres which is based on their solubility in water (Buttriss & Stokes, 2008; Jia et al., 2020). Purported therapeutic effects of insoluble fibres are that they aid in laxation, regularity and are seldom fermented in the large intestine. Whereas soluble fibres reduce serum cholesterol, reduce glucose absorption, increase satiation, and are readily fermented (Foschia et al., 2013; Tang et al., 2024; Widaningrum et al., 2020). This current classification does not adequately account for dietary fibre's complexity and therapeutic effects. The simplicity of the current classification system needs to be advanced to a comprehensive system that accounts for various fibre structure and improves health effect deduction. This perspective article proposes a framework for describing different dietary fibres and their related physiological effects.

Table 1
Types of dietary fibre.

Fibre type	Description	Reference
Cellulose	Composed of D-glucose units linked by β (1–4)-glycosidic bonds in a linear homopolymer which can reach up to 10 000 units long.	(Buttriss & Stokes, 2008; Gupta et al., 2019)
Hemicellulose	Branched with acetyl group side chains and a backbone consisting of monomers – xylose, arabinose, galactose, mannose or glucose.	(Debnath et al., 2021; Kumar & Dixit, 2021)
Lignin	Not a polysaccharide but is mainly composed of alcohols (p-coumaryl, coniferyl, and sinapy) or collectively known as phenylpropanoid units.	(Kumar & Dixit, 2021)
Gums	Gums are plant exudates that having varying structures and physiochemical properties.	(Amiri et al., 2021; Hamdani et al., 2019)
Beta- glucans	It is a non-starch polysaccharide that can be branched or unbranched and is β-D-glucose monomer units linked by glycosidic linkages at β (1 → 3), (1 → 4), and/or (1 → 6). There are numerous hydroxyl groups along the β −glucan chain which create a hydrophilic molecule.	(Kaur et al., 2020; Wood, 2007)
Resistant starches	Resistant starches are comprised of starches that do not have their α-1,4-glycosidic bonds hydrolysed by salivary and pancreatic α-amylases which pass unabsorbed into the large intestine where it can be fermented. There are 5 types of resistant starch: RS 1 which is physically inaccessible starch due to being enclosed within the food's structure RS 2, a native starch granule which can be found in unripe bananas and raw potato. RS 3 is a retrograded starch RS 4 is a starch that has been chemically modified to resist digestion such as a starch with octenyl succinic groups. RS 5 occurs when amylose complexes with lipids or fatty acids during cooking – resulting in the starch being trapped in a amylose–lipid complex.	(Birt et al., 2013; Bojarczuk et al., 2022; Buttriss & Stokes, 2008; Dobranowski & Stintzi, 2021; Gutiérrez & Tovar, 2021)
Non-digestible oligosaccharides:	Low molecular weight carbohydrates with monomeric units between 3 and 10 which are recalcitrant to digestion by salivary and intestinal enzymes.	(Mussatto & Mancilha, 2007)

2. Ambiguities and shortcomings of the current dietary fibre classification

The binary classification of fibres into soluble and insoluble categories is practical for isolated fibre studies but fails to capture the complexities of fibres within mixed food systems. Pure fibre's homogenous nature makes its effects predictable, making it useful within the food industry. However, accurately determining physiological effects from this classification is ineffective, considering that foods consist of multiple fibre types and are not consumed individually. This binary classification into soluble and insoluble inadequately encapsulates the diverse structures and multifaceted mechanisms by which dietary fibres act on human physiology (Guillon & Champ, 2000; Harris et al., 2023; Khorasaniha et al., 2023; Qin et al., 2021; Ratanpaul et al., 2023; Slavin, 2013; Stribling & Ibrahim, 2023; Williams et al., 2017; Williams et al., 2019). Realistically, fibre intake is consumed in a whole food system that consists of both categories of fibres, creating a situation where every food containing fibre is described as soluble and insoluble with different percentages of each; thus, the functional effects become unclear. For example, pectin, typically classified as soluble, demonstrates insoluble-like behaviour when integrated into complex matrices, illustrating the fluidity of fibre categorization based on physical interactions (Buttriss & Stokes, 2008). Moreover, purified fibre fermentability is not representative of a composite food system. A purified fibre provides the microbiota more access to the fibre structure, which will affect the microbiota along the gastrointestinal tract (GIT) differently than in a composite food system (Williams et al., 2017).

It is commonly purported in the literature that soluble fibres are readily fermented, and insoluble fibres are not, but this is only occasionally true. Examples of incongruity include that soluble psyllium fibre being partially fermentable, cereal flours that can have similar fermentation profiles of both soluble and insoluble fibres, and completely insoluble cellulose and lignin can be fermented to an extent in the human colon (Carlsen & Pajari, 2023; Gidley & Yakubov, 2019; Harris et al., 2023; Widaningrum et al., 2020). Additionally, the current classification implies that only soluble fibres inhibit α-amylase, but both insoluble (e.g., cellulose) and soluble (e.g., guar gum) can inhibit α-amylase activity, albeit through different mechanisms. Where α-amylase binds to cellulose with a mixed inhibition mechanism and is physically prevented from accessing a substrate in the presence of guar gum. (Dhital et al., 2015; Gill et al., 2021). Clinical studies on dietary fibres' effectiveness on blood pressure have given contradicting results. A systematic review by Khan et al. found that soluble fibres can affect systolic and diastolic blood pressure differently. For example, psyllium can significantly reduce blood pressure, whereas konjac glucomannan does not (Khan et al., 2018). However, data from cohort studies such as the international study on macro/micronutrients and blood pressure (INTERMAP) suggested that insoluble fibre reduces blood pressure by up to 1.81 mmHg systolic blood pressure if 4.6 g/4184 kJ of insoluble fibre is consumed. In contrast, soluble fibre has no effect (Aljuraiban et al., 2015). The umbrella description of some dietary fibres as "soluble" makes it unclear what exactly is causing clinical effects. Moreover, a binary classification poorly accounts for resistant starch and its physiological effects. Resistant starch solubility varies from insoluble for type 1 to medium solubility for type 5 while all being fermentable (Aljuraiban et al., 2015; Carlsen & Pajari, 2023; Li et al., 2024). Additionally, some resistant starch and inulin do not lower blood cholesterol, and oat bran increases stool weight although they are all soluble fibres (Slavin, 2013). Pectin can be either soluble or insoluble depending on what ions or other insoluble polysaccharides it has bound to (Hirst & Jones, 1946). Finally, no part of the classification accounts for the possibility that a fibre can be constipating, and so the constipating effects of fine wheat bran's effects are undefined (McRorie et al., 2020).

The current classification also does not account for modified or treated fibres. Food items often undergo processing before being consumed, from heating and cooling to chemical treatments. Treatments can be chemical, for example, using ascorbic acid which reduces viscosity (Kaur et al., 2020; Tang et al., 2024; Zhang et al., 2020). These treatments can break the glycosidic bonds and change the fibres matrix (Zhang et al., 2020). Processing techniques, including heat and enzymatic treatments, can alter fibre solubility and functionality, challenging the traditional classification system. Treatments extend to enzymatic, physical and combined methods, which significantly impact the fibre's physiochemical properties and can change the ratio of insoluble to soluble fibres (Iqbal et al., 2022; Jia et al., 2020; Williams et al., 2019). Modifications can alter the properties of fibre, although it does not affect all fibres equally. For example, increased branching decreases solubility of β-glucan, but increases solubility for amylopectin (Gill et al., 2021; Kaur et al., 2020; Tang et al., 2024; Zhang et al., 2020). As such, a comprehensive fibre classification needs to account for the different functional effects fibre modifications can have.

There are multiple methods for determining the different materials that can be classified as dietary fibre. The methods, AOAC 993.43 and AOAC 2011.43 determine total dietary fibre, insoluble and soluble dietary fibre whereas AOAC 2011.25 determines resistant starch. Although these methods are standard practice, their results vary significantly. In a comparison study of wheat, soybean meal, rapeseed meal, sugar beet pulp, peas, horse beans, native pea starch, and two samples of corn between 3 laboratories, both the AOAC 993.43 and AOAC 2011.25 gave similar results for the total dietary fibre. However, the insoluble dietary fibre content was higher for corn, wheat, peas, and sugar beet pulp than the AOAC 2011.43 results. Moreover, the soluble fibre content was higher using 2011.43 for corn, rapeseed meal, soybean meal, and sugar beet pulp compared to AOAC 993.43 (Nguyen et al., 2019). Similarly, Tobaruela et al. compared the total fibre content between AOAC 2011.43 and AOAC 991.43 among plums, atemoyas, jackfruits and mature coconuts. They concluded that AOAC 991.43 underestimates the fibre content due to not accounting for low molecular weight soluble dietary fibres (Tobaruela et al., 2018). The same conclusion was drawn by Frejancic et al. when testing 45 different foods consisting of fruits, vegetables, grains and legumes (Ferjančič et al., 2022). The methodologies currently in place for dietary fibre solubility analysis are time-consuming and are only sometimes comparable to other results.

Currently, the simplicity of fibres' characterisation has led to other terms being created to describe dietary fibres functionally and in more detail. The term "microbiota-accessible carbohydrates" or MACs is one of these terms, used to describe intestinally undigested carbohydrates that are degraded by microbes in the gastrointestinal tract (Ayakdaş & Ağagündüz, 2023; Sonnenburg & Sonnenburg, 2014). Critically, this term focuses on how fibres interact with the microbiome (Williams et al., 2019). The concept of microbiota-accessible carbohydrates (MACs) focuses on utilising carbohydrates by gut bacteria. Given the interpersonal gut microbiome variability, a MAC for one person might not be the one for another (Deehan et al., 2017). For example, Japanese individuals have a microbiome suited to the digestion of porphyrin, while most North Americans and Europeans do not (Ayakdaş & Ağagündüz, 2023). Similarly, lactose is a MAC for individuals with lactose intolerance, not those who can digest lactose (Sonnenburg & Sonnenburg, 2014).

3. Dietary fibre characteristics and properties considered for an enhanced classification system

Understanding the characteristics and properties of dietary fibre is essential for developing an enhanced classification system. Various analytical techniques provide detailed information about the molecular structure and physicochemical properties of dietary fibre, which directly influence its physiological functions and health benefits. Methods such as X-ray photoelectron spectroscopy, Raman spectroscopy, Fourier-transform infrared spectroscopy, and X-ray diffraction can provide structural information on elemental composition, chemical bonds, functional groups, and crystalline structure, respectively (see Table 2 for a summary of these instruments' utilities and limitations). Additionally, the surface morphology and overall shape of dietary fibre determine how it interacts with the environment and biological system (Widaningrum et al., 2024). Techniques such as scanning electron microscopy (SEM) and atomic force microscopy (AFM) can assess surface morphology, while small-angle X-ray scattering (SAXS) can determine the shape and size of crystallized compounds. Table 3 summarizes these techniques and their applications.

Dietary fibre exerts a variety of practical effects that lead to beneficial health outcomes, which are important considerations for classification. Fiber can bind significant amounts of water—up to 56 g of water per gram of pectin fibre—beneficially increasing stool output and promoting regular bowel movements (Alison & Cummings, 1979). Other effects include binding bile acids and luminal cholesterol to reduce serum cholesterol levels, as well as binding glucose to mitigate post-prandial glucose increases (Lupo et al., 2022; Ötles & Ozgoz, 2014). By affecting lipid and glucose metabolism, these characteristics can contribute to weight management and reduce the risk of metabolic diseases. Additionally, fibre can bind toxic ions such as lead and arsenic,

Table 2
Techniques to determine structural characteristics of dietary fibres.

Techniques	Utility	Limitations	Reference
Electron diffraction	Lattice systems	Requires thin samples	(Li & Sun, 2017; Rongpipi et al., 2019)
Raman spectroscopy	Chemical functionality, molecular conformation, H-bonding	Weak O–H vibrations	(Kim et al., 2013; Panczer et al., 2012; Rongpipi et al., 2019)
X-ray photoelectron spectroscopy	Hydrophobicity, elemental composition, bonds	Only measures surface layer (1 nm – 10 nm)	(Anette et al., 2006; Dogan et al., 2015)
Fourier-transform infrared microscopy	Functional groups	Strongly detects water	(Qadir & Wani, 2022; Rongpipi et al., 2019)
X-ray diffraction	Crystallinity	Can damage sample	(Djordjević et al., 2022; Rongpipi et al., 2019)
Neutron diffraction	Crystalline structure	Requires high sample volume and long measurement times	(Martínez-Sanz et al., 2017; Rongpipi et al., 2019)
Nuclear magnetic resonance	Linkage analysis, 3D structure.	Requires large sample volume and long measurement times	(Hell et al., 2014; Rongpipi et al., 2019; Haslam et al., 2022)
Sum frequency generation	2D structure, 3D system	Sensitive to non-centrosymmetric environments	(Choi et al., 2022; Rongpipi et al., 2019)

Table 3
Instruments and their utility for determining morphological characteristics of dietary fibres.

Techniques	Utility	Limitations	Reference
Scanning electron microscopy	Porosity, shape and particle arrangement, roughness	Limited to nm resolution	(Tang et al., 2024; Xie et al., 2019)
Transmission electron microscopy	Shapes of individual fibres	Extensive sample preparation	(Ullah et al., 2017)
Atomic force microscopy	Surface morphology	Works best on flat samples.	(Morris et al., 2011; Rongpipi et al., 2019)
Small angle X-ray scattering	Size, shape and microfibril angle	Functions between 1 nm – 100 nm	(Gilbert, 2019; Rongpipi et al., 2019)
Small angle neutron scattering	Size and shape	Requires large sample volumes and longer measuring times	(Gilbert, 2019; Rongpipi et al., 2019)

aiding in their excretion and reducing their bioavailability (Wang et al., 2015). Fermentation of dietary fibre in the colon produces short-chain fatty acids, which can inhibit cancer metastasis and beneficially modulate the immune system (Dong et al., 2023). Table 4 summarizes properties of dietary fibre that can be tested, which have direct implications in identifying fibres with specific health-promoting effects.

Table 4
Functional properties and effect of dietary fibre.

Property	Affect	Reference
Water-holding-capacity	Decreases food intake, stool bulking and regularity.	(Dhingra et al., 2012; Liu et al., 2020; Raghavendra et al., 2004; Tejada-Ortigoza et al., 2016)
Glucose-absorption-capacity	Capturing and binding glucose	(Liu et al., 2020)
Bile-acid-binding-capacity	Capturing bile-acids	(Liu et al., 2020; Wood, 2007)
Viscosity	Delay gastric emptying, reduce rate of glucose, and bile acid absorption	(Lupo et al., 2022; Tang et al., 2024)
Cholesterol-binding-capacity	Ability to bind cholesterol	(Wood, 2007)
Anti-tumour activity	Cytotoxicity towards cancer cells	(Tang et al., 2024)
Fermentability	Metabolite production and microbiota modulation	(Cronin et al., 2021; Jonathan et al., 2012)
Immunomodulatory activity	Regulating immune response	(Dong et al., 2023; Tang et al., 2024)
Swelling	Affects regularity and stool bulking.	(Dhingra et al., 2012; Raghavendra et al., 2004; Tang et al., 2024)
Particle size	Affects binding ability and fermentation of fibre	(Dhingra et al., 2012)
Gelling capacity	Increased satiation	(Wanders et al., 2013)
Oil-holding capacity	Mouthfeel and taste	(Siddiqui et al., 2023)
Adsorption of toxic ions	Binding of toxic elements	(Wang et al., 2015)
Cation absorption capacity	Binding of glucose and lipids	(Gupta & Premavalli, 2011)
Zeta potential	Matrix stability, ion binding, folding	(Gu et al., 2020)

4. The microbiome and its relevance to the alimentary effects of dietary fibre

The human gastrointestinal tract harbors approximately 10^{14} bacteria, which are unevenly distributed throughout the gut and surpass the estimated number of human cells in the body (Nicholson et al., 2012; Wang et al., 2018). The predominant bacterial phyla in the gastrointestinal tract are *Firmicutes* (58–88 %), *Bacteroidetes* (8.5–28 %), *Proteobacteria* (0.1–8 %), and *Actinobacteria* (2.5–5 %). However, it is suggested that up to 60 % of bacterial species have not yet been identified (Williams et al., 2019). The small intestine is primarily colonized by bacteria from the genus Lactobacillus and the family Enterobacteriaceae, while the colon is predominantly inhabited by members of the families Bacteroidaceae, Prevotellaceae, Rikenellaceae, Lachnospiraceae, and Ruminococcaceae (Luo et al., 2021; Rinninella et al., 2019). These microbial communities encode an extensive repertoire of carbohydrate-active enzymes (CAZymes), including over 130 families of glycoside hydrolases (GHs) that break down glycosidic linkages within carbohydrates, 22 families of polysaccharide lyases (PLs) capable of cleaving polysaccharides via beta-elimination, and more than 60,000 carbohydrate-degrading enzymes capable of processing various plant-based materials, including dietary fibre (Ayakdaş & Ağagündüz, 2023; Sonnenburg & Sonnenburg, 2014). In contrast, the human genome encodes only 87 GHs, which collectively degrade a limited range of substrates such as polysaccharides, oligosaccharides, proteoglycans, glycoproteins, and glycolipids (Hansen et al., 2020). The variety of degrading enzymes produced by the microbiota is required to effectively ferment the complex structures of dietary fibres. Individual bacteria can cleave specific linkages, necessitating a diverse gut environment to successfully degrade the heterogeneous structures of dietary fibres (Fang et al., 2023; Zhang, 2022).

Fermentation of dietary fibre occurs predominantly in the colon, producing various metabolites, among which short-chain fatty acids (SCFAs) such as acetate, propionate, and n-butyrate are significant components, present in an approximate ratio of 60:20:20, respectively (Silva et al., 2020). Most SCFAs are absorbed by colonocytes and can contribute up to 10 % of our daily energy intake (den Besten et al., 2013; Gamage et al., 2018). Short-chain-fatty-acid production depends on the available substrates and the bacterial species present. Butyrate is mainly produced by bacteria belonging to the genera Clostridium, Eubacterium, and Roseburia, and it has many important functions within the body. These include serving as the primary energy source for colonocytes, possibly stimulating leptin production, and inducing the secretion of glucagon-like peptide-1. Butyrate also exhibits anti-inflammatory actions, regulates neutrophil function, and can be metabolized by colonocytes to produce ketone bodies and carbon dioxide (Nicholson et al., 2012). Most SCFAs are produced in the proximal colon; however, fibres provide a more significant health benefit when they are fermented more distally in the colon, which is where most colorectal cancers occur (Barber et al., 2020; Carlsen & Pajari, 2023; Nicholson et al., 2012; Rose et al., 2007). Consequently, dietary fibre is an instrumental component in mediating the microbiota and promoting intestinal and overall health, affecting microbial communities throughout the gastrointestinal tract—from the oral cavity to the rectum (Anderson et al., 2009; Buttriss & Stokes, 2008; Cronin et al., 2021; Gill et al., 2021; Hou et al., 2022; Li & Komarek, 2017; Oz et al., 2023; Sedghi et al., 2019).

5. A novel dietary fibre framework for dietary fibre classification to accurately determine health outcomes

Given the complexity of dietary fibre structures and their range of functional effects, a robust framework needs to be created to better interpret and utilize them. Such a system can aid clinicians and consumers in understanding which fibres should be consumed to reduce what is described as the “fibre gap.” Additionally, researchers can benefit by identifying which aspects of fibre need further development for enhanced therapeutic potential (Cantu-Jungles & Hamaker, 2020; Deehan et al., 2017; Pieper et al., 2015). The fibre gap describes the difference between the amount of fibre consumed by the populace and the recommended intake (Fuller et al., 2016; Jones, 2014; Stephen et al., 2017). The recommended dietary fibre intake is 28–42 g per day, while the median intake is 12–14 g per day for Americans and 18–24 g per day in European countries (Stephen et al., 2017; Thompson & Brick, 2016).

Successful development of an accurate classification requires that multiple fundamental properties be included. This novel classification framework selects properties that account for various aspects of fibre consumption, including its native structure, interactions with the surrounding environment, and the effects of its degradation—a "bottom-up" approach that utilizes fundamental aspects to determine overall effects. A summary of the incorporated categories is presented in Table 5 and depicted in Fig. 1. The bottom-up approach comprises five categories with multiple subcategories, creating a high-fidelity understanding of a fibre substance. This robust categorization framework applies to both purified and composite samples, such as fibre supplements or foods.

Firstly, the dietary fibre backbone is categorized based on whether it is a branched structure and its degree of polymerization (DP). Including backbone length via DP makes the classification applicable worldwide, since dietary fibre definitions differ between countries based on DP, allowing individual countries to select which fibres to include. As such, this classification can enable harmonious and translatable data between countries with different dietary fibre definitions (de Menezes et al., 2013). The DP and branching affect important characteristics like swelling, water-holding capacity, stool bulking, and slowing nutrient absorption (Li et al., 2024). Branched fibre structures have greater stearic hindrance between their bonds, affecting their ability to emulsify fats, bind water and affect viscosity. DP is associated with modulating different bacteria species, altering the metabolites that are produced (Chen et al., 2020; Van De Wiele et al., 2007). Higher branched structures positively modulate beneficial bacteria such as Bacteroides, Lachnospira, and Phascolarctobacterium, while negatively modulating harmful bacteria such as Fusobacterium and Paeniclostridium (Li et al., 2024), whereas shorter structures increase bifidobacterial growth (Ho et al., 2018). Therefore, the *backbone structure* indicates the branching and chain length that a fibre contains. Branching is subcategorized into *linear*, *branched*, and *both*, whereas chain length is split into *short* fibres with DP less than 10 and *long* fibres with DP more than 10 (Agamennone et al., 2023; Ho et al., 2018; Tungland & Meyer, 2002). This category is more practical for purified samples due to their homogeneous nature, in contrast to whole foods that contain branched and unbranched fibres of various lengths (McRorie, 2015).

Dietary fibre structures can contain functional groups that can become charged, such as carboxyl groups from uronic acids and phenolic acids in lignin. These negatively charged functional groups enhance fibre's ability to bind toxic cations (e.g., arsenic or lead), facilitate cation exchange, increase its solubility and water-holding capacity, improve emulsifying ability, and increase glucose adsorption capacity. Additionally, a lower surface charge increases alpha-amylase inhibition (Zhang et al., 2023). Although charged sites increase swelling capacity and water-holding capacity, they are not as conducive to proliferating Bifidobacterium and Lactobacillus species as neutral carbohydrates. However, lower charge increases the production of butyrate and acetate (Guillon & Champ, 2000; Li et al., 2024; Qiao et al., 2021; Thebaudin et al., 1997), whereas higher charge creates more stable solutions (Gu et al., 2020; Gupta & Premavalli, 2011; Meĭchik et al., 2011; Ullah et al., 2017; Yang et al., 2024). Carbohydrate charge is predicated upon the functional groups present within its structure, namely, carboxyl groups, phenolic groups, and sulphate groups. Understanding the charged groups present allows inference of the overall charge and can be experimentally quantified. The second category is the structure charge, split into *negative, neutral*, and *positive*, indicating the effective charge of the fibre at neutral pH (the luminal pH of the small intestine).

The fibre matrix can be defined as the physical state of the fibre once it enters the stomach. The fibre matrix has significant implications for fibre's hydration properties, satiation effects, glycaemic control, lipid control, and effects on the microbiota. Gelled matrices can more effectively absorb water, glucose, and cholesterol, and are readily fermented by the intestinal microbiota. The converse holds for more rigid matrices, which remain unchanged once they have entered the intestinal tract (Li et al., 2024; Raghavendra et al., 2004). Composite foods, which contain a mix of fibres and other substances, can be described as aggregates, where a coalescing suspension is formed. The third category is *fibre matrix* and describes the structural integrity as it passes through the gastrointestinal tract, subcategorized into *rigid, gel,* and *aggregate*, delineating important physical states (Qin et al., 2021).

Fermentation rate denotes the speed at which fibres are fermented in the large intestine. This category accounts for aspects such as the degree of methylation of fibres and the terminal ends of fibre structures, which affect the fermentation rate and quantify SCFA production (Wang et al., 2019). The speed at which a fibre ferments can indicate the intestinal discomfort experienced due to bloating and is a key determinant in fibre functionality (Ratanpaul et al., 2023). Furthermore, it reflects gut bacteria's ability to degrade the carbohydrates and produce SCFAs. Fibers that are not fermented until they reach the distal colon could provide more alimentary effects, as most colorectal cancers originate distally (Kaur et al., 2011; Van De Wiele et al., 2007). The fourth category is *fermentation rate*, accounting for the effect of microbiota interacting with dietary fibre, with two sections: rapidly fermented fibres, which are completely fermented in the proximal colon, and slowly fermenting fibres, which are not entirely fermented in the proximal colon, thereby reaching the distal colon (Stribling & Ibrahim, 2023).

Lastly, *water-holding-capacity* (WHC) indicates the amount of water retained by a fibre without the application of external forces beyond atmospheric pressure and gravity. WHC is crucial for determining the health effects of dietary fibres. The capacity to retain water aids in stool softening, increases viscosity, prolongs transit time in the stomach and small intestine, and decreases transit time in the large intestine. WHC can also serve as a proxy for the absorption of other nutrients and may indicate microbial community evenness. Factors influencing WHC include particle size, surface area, shape, porosity, and charge (Alison & Cummings, 1979; Brownlee, 2011; Raghavendra et al., 2006; Takahashi et al., 2009). WHC can be categorized as follows: *low* for substances that hold less than 2 g of water per gram of dry matter, *medium* for those that hold between 2 and 10 g of water per gram of dry matter, and *high* for food matrices that retain more than 10 g of water per gram of dry matter.

Table 5
Enhanced dietary fibre classifications.

Characteristic	Sub-category
Backbone structure (isolated fibres)	a) Chain Structure i. Linear ii. Branched iii. Both b) Chain length i. Short DP $<$ 10 ii. Long DP $>$ 10
Structure charge	a) Negative b) Neutral c) Positive
Fibre matrix	a) Rigid b) Gel c) Aggregate
Fermentation rate	a) Slow b) Fast
Water-holding-capacity	a) Low ($<$2 g/g) b) Medium (2–10 g/g) c) High ($>$ 10 g/g)

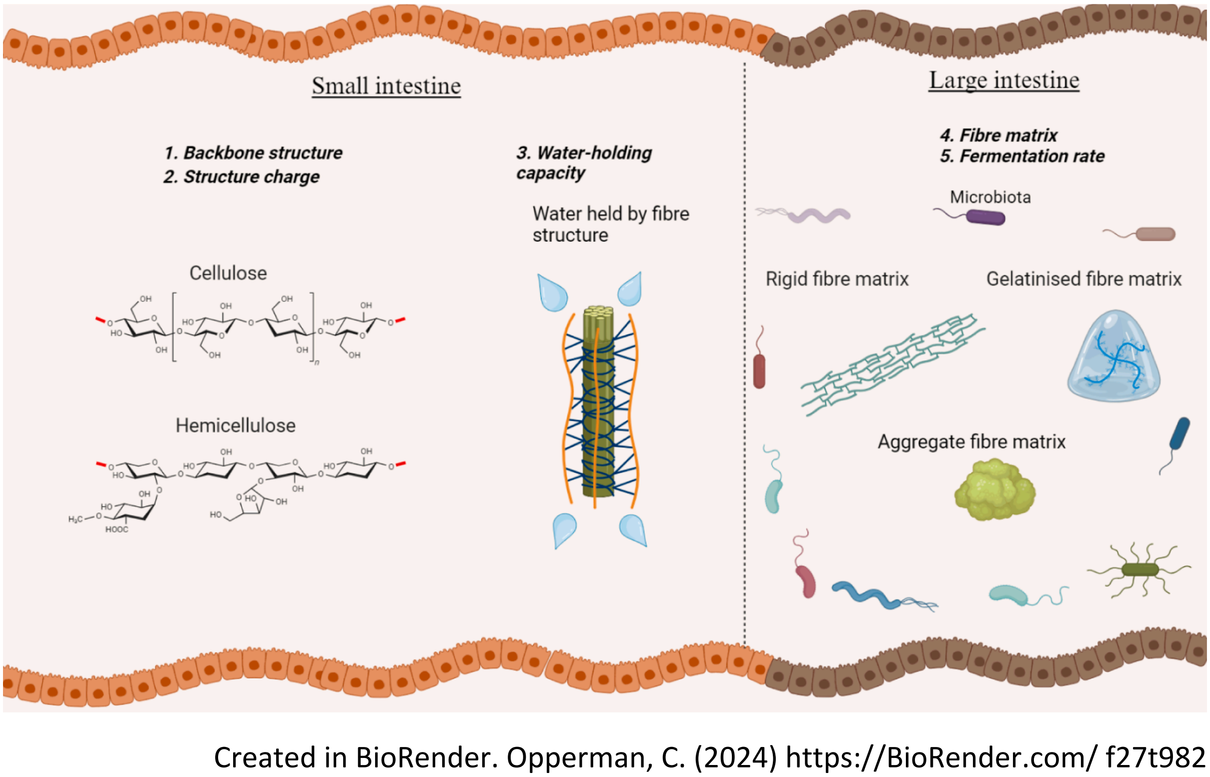

Fig. 1. Visualising the *bottom-up approach* within a truncated intestinal system. The figure depicts a molecular structure of cellulose and hemicellulose, highlighting free charges on each side of the structures. Water-holding-capacity is illustrated by a fibre structure attracting water. In the large intestine section of the diagram different fibre matrixes are shown surrounded by gut bacteria.

6. Utilising the *bottom-up approach*

To understand the practicality, efficacy, and versatility of the bottom-up approach, we compare the outcomes of the previous classification system—soluble and insoluble fibres—with the new multipoint system. We will examine distinct types of dietary fibres: cellulose, guar gum, pineapple pomace, and type II resistant starch (RS2). Under the current system, pure cellulose is described as an insoluble fibre with inferred health benefits such as increasing stool moisture content and stool bulk, and it is not fermented by the gut microbiota. Guar gum is described as soluble, with inferred benefits including reducing blood glucose and cholesterol levels and being rapidly fermented by the microbiota. Pineapple pomace cannot be accurately described by the current system due to its complex composition. Type II resistant starch is classified as insoluble, suggesting it would have similar health benefits to cellulose. The *bottom-up* approach adds crucial details for health effect induction. Below the *bottom-up* approach is utilised to describe cellulose, guar gum, pineapple pomace and RS2.

The bottom-up approach adds crucial details for understanding health effects. Below, this approach is utilized to describe cellulose, guar gum, pineapple pomace, and RS2.

Cellulose

1. Fermentation rate – Slow (Wang et al., 2019)
2. Backbone structure – Linear with long chains (McNamara et al., 2015)
3. Charge – Neutral
4. Fibre matrix – Rigid
5. Water-holding-capacity – Medium (Chau et al., 2008)

Cellulose has a low fermentation rate and requires specific bacteria for its degradation, such as Ruminococcus champanellensis. Slow fermentation supplies SCFAs effectively along the length of the large intestine (Moraïs et al., 2016; Moraïs et al., 2024). Its molecular structure is a long and linear chain, indicating low solubility and fermentation but usefulness in aiding stool bulk. The neutral charge suggests it may not strongly adhere to cations. Cellulose remains a rigid structure once consumed, further indicating low binding ability for trapping intestinal molecules. Its medium water-holding capacity makes it suitable for aiding stool softening and inducing satiety.

Unmodified guar gum

1. Fermentation rate – Slow
2. Backbone structure – branched long chains.
3. Charge – Neutral
4. Fibre matrix – Gel
5. Water-holding-capacity – High

Unmodified guar gum is a slowly fermenting fibre and a branched long-chain molecule, indicating that Bifidobacteria are less likely to ferment it. However, Clostridium butyricum can completely degrade guar gum. A slower fermenting fibre will be fermented more distally in the colon. Guar gum is composed of linked mannose monomers with branched galactose monomers and contains no carboxyl or phenolic groups, indicating a neutral charge. This leads to a low potential for binding ions such as lead, mercury, and bile salts. When consumed, guar gum dissolves in water and forms a gel, allowing it to entrap glucose, amylase, and cholesterol. Guar gum has a high water-holding capacity (WHC) of 40 g water/g gum, giving it a great ability to moisten stool and aid in inducing satiety.

Pineapple juice pomace

1. Fermentation rate – High
2. Backbone structure – Branched long chains.
3. Charge – Negative
4. Fibre matrix – Aggregate

5. Water-holding-capacity – Medium

Understanding more complex and composite structures helps in comprehending the effects that fibre-containing foods can have on the body. Categorizing a whole food such as pineapple juice pomace is different from categorizing purified samples, as the whole food contains a variety of compounds and can be processed in ways that change its properties. Regardless, the categorization process remains the same. Pineapple pomace has a slow fermentation rate (Widaningrum et al., 2024). Due to its content of cellulose, hemicellulose, lignin, and small amounts of pectin, it cannot be solely described as linear or branched; thus, this category can be omitted. Pineapple pomace has high quantities of phenolic compounds, contributing to a negative charge and giving it a high potential to bind toxic cations and bile salts (Cardona et al., 2022; Mohd Ali et al., 2020). The fiber matrix is aggregated, aiding in its ability to bind, obstruct, and adhere to glucose, α-amylase, etc., which, given its tight packing and composition, can obstruct bacterial degradation[4]. Pineapple pomace has a medium WHC of 5.32 g water/g pomace (Widaningrum et al., 2024). Pineapple pomace has a medium WHC of 5.32 g(water)/g(pomace) (Selani et al., 2014), making it capable of softening stool and aiding in the attenuation of glucose and cholesterol absorption.

Type 2 resistant starch

1. Fermentation rate – Slow
2. Backbone structure – Branched long chains.
3. Charge – Neutral
4. Fibre matrix – Aggregate
5. Water-holding-capacity – Low

There are five types of resistant starch, each resistant due to a different mechanism. This example focuses on RS2. RS2 is slowly fermentable, and its structural nature and composition lead to fermentation that yields a higher abundance of Bifidobacterium, Ruminococcus bromii, Eubacterium rectale, Bacteroidetes, and Actinobacteria (Haghighatdoost et al., 2021; Tiwari et al., 2019). RS2 is composed of linear glucose molecules that are semi-crystalline and compact (Joye, 2019), indicating low binding potentials and slow digestibility. RS2 has no charged functional groups and is neutral, reducing its ability to bind ions, glucose, and cholesterol. Due to its compact structure and its matrix during digestion, it can be classified as an aggregate. It has low WHC, which lowers its ability to moisten stool and possibly attenuate glucose and cholesterol absorption.

The examples categorizing cellulose, guar gum, pineapple pomace, and resistant starch provide a basis for the versatility of the proposed classification framework and demonstrate its ability to predict the physiological effects of consuming these foods more accurately.

7. Final remarks

Since its initial definition in 1953, the concept of dietary fibre has undergone significant evolution. While substantial efforts have been made to clarify its definition, the development of classification systems has been neglected, resulting in an overly simplistic binary categorization of fibres as either soluble or insoluble. This dichotomy fails to account for the diverse structures and physicochemical functionalities of dietary fibres, limiting our understanding of their varied health effects.

This article proposes a comprehensive categorization framework—*the bottom-up approach*—that encompasses the quintessential properties of dietary fibres and subcategorizes them for a higher-resolution understanding. By considering factors such as molecular backbone structure, charge, fibre matrix, fermentation rate, and water-holding capacity, this framework provides a nuanced classification that better reflects the complexity of dietary fibres.

Utilization of this approach can aid consumers, researchers, and clinicians in identifying which aspects of dietary fibres are most important for specific health outcomes. It enables a more precise correlation between fibre characteristics and their physiological effects, facilitating targeted dietary recommendations and the development of functional foods with enhanced therapeutic potential. Additionally, the bottom-up approach introduces a new paradigm for interpreting and understanding dietary fibres, paving the way for advancements in nutrition science and public health.

CRediT authorship contribution statement

Christo Opperman: Writing – original draft, Conceptualization. **Mahsa Majzoobi:** Writing – review & editing. **Asgar Farahnaky:** Writing – review & editing. **Rohan Shah:** Writing – review & editing. **Thi Thu Hao Van:** . **Vishal Ratanpaul:** Writing – review & editing. **Ewan W. Blanch:** Writing – review & editing. **Charles Brennan:** Writing – review & editing. **Rajaraman Eri:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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