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Narrative Review

Dietary fibre definition revisited - The case of low molecular weight carbohydrates

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SUMMARY

Low molecular weight (LMW) non-digestible carbohydrates (namely, oligosaccharides and inulin) are accepted as dietary fibre in many countries worldwide. The inclusion of oligosaccharides as dietary fibre was made optional within the Codex Alimentarius definition in 2009, which has caused great controversy. Inulin is accepted as dietary fibre by default, due to being a non-digestible carbohydrate polymer. Oligosaccharides and inulin occur naturally in numerous foods and are frequently incorporated into commonly consumed food products for a variety of purposes, such as to increase dietary fibre content.

LMW non-digestible carbohydrates, due to their rapid fermentation in the proximal colon, may cause deleterious effects in individuals with functional bowel disorders (FBDs) and, as such, are excluded on the low FODMAP (fermentable oligosaccharides, disaccharides, and polyols) diet and similar protocols. Their addition to food products as dietary fibre allows the use of associated nutrition/health claims, causing a paradox for those with FBDs, which is further complicated by lack of clarity on food labelling. Therefore, this review aimed to discuss whether the inclusion of LMW non-digestible carbohydrates within the Codex definition of dietary fibre is warranted.

This review provides justification for the exclusion of oligosaccharides and inulin from the Codex definition of dietary fibre. LMW non-digestible carbohydrates could, instead, be placed in their own category as prebiotics, recognised for their specific functional properties, or considered food additives, whereby they are not promoted for being beneficial for health. This would preserve the concept of dietary fibre being a universally beneficial dietary component for all individuals.

1. Introduction

Consumption of dietary fibre has long been associated with decreased risk of cardiovascular disease, diabetes, obesity, and colorectal cancer, and maintenance of colonic health and gut motility [1,2]. Such associations stem from consumption of wholegrains, fruits, and vegetables, which are naturally high in dietary fibre, mostly comprising non-starch polysaccharides (NSP), which originate in the plant cell wall. Thus, consumption of these food groups is strongly advocated through public health messages.

Early definitions of dietary fibre included only non-digestible components of the plant cell wall (namely NSP) [3], but more recent definitions now include any edible parts of the plant or analogous (extracted/synthetic) carbohydrates that are resistant to digestion in the small intestine and fermented in the large intestine [4]. Such expansions have led to the inclusion of non-digestible oligosaccharides within many definitions; their inclusion has been adopted by the EU, UK, US and many other countries and was made optional within the Codex Alimentarius Commission definition in 2009 [5]. Oligosaccharides are a category of short-chain carbohydrates, which are considered low molecular weight (LMW) dietary fibre [6] and are plant energy reserves found naturally in wheat-based grains, pasta, bread, pulses, and legumes. Oligosaccharides are primarily associated with their microbial effects, rather than their effects on bowel function, and there has been great controversy regarding their classification as dietary fibre. Inulin is also classed as LMW dietary fibre, in either its oligosaccharide or polysaccharide form [6–8], and is accepted as dietary fibre within the Codex definition by default due to being a natural non-digestible carbohydrate polymer.

Low intakes of dietary fibre are a feature of a typical ‘Western’ diet [9], which is high in saturated fat, refined sugar, and salt, and

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low in fibre-containing plant-based foods. This is a worldwide concern, and only 9% of adults in the UK are reaching the recommended dietary fibre intake of 30 g per day [10]. Thus, there have been attempts to increase dietary fibre content of commonly consumed food products using extracted/synthetic fibre (such as oligosaccharides and inulin), allowing the adoption of nutrition and health claims on food labelling [11]. The health effects of extracted/synthetic fibre versus intrinsic fibre are unknown, and food labelling does not distinguish between intrinsic or added fibre, which may be confusing for consumers.

Extracted/synthetic oligosaccharides and inulin can be added in high quantities to food products, not only to modify fibre content, but also as sweeteners, fat replacers, texture modifiers, and humectants, which has great implications for those with functional bowel disorders (FBDs). FBDs affect over 33% of the population [12] and are associated with reduced quality of life [13] and large healthcare costs [14]. LMW dietary fibre consumption is associated with bloating, abdominal pain, and excess flatus in these individuals [15], and oligosaccharides and inulin are the main components excluded during the low FODMAP (fermentable oligosaccharides, disaccharides, monosaccharides, and polyols) diet, a widely used dietary therapy to assist with symptom relief in those with FBDs. Thus, due to the impact caused to those with FBDs, this review aims to discuss whether the inclusion of non-digestible LMW carbohydrates (i.e. oligosaccharides and inulin) within the Codex definition of dietary fibre is warranted.

2. Overview of dietary fibre

2.1. History of dietary fibre

Establishing a universal definition for dietary fibre is paramount for health regulations and public health messages, nutritional labelling, nutritional databases, comparisons of fibre intakes, and interpreting research [16]; however, numerous definitions exist worldwide and there is currently no universally accepted definition. Dietary fibre was first defined by Hipsley in 1953 when a link was discovered between low dietary fibre intake and increased occurrence of toxaemia in pregnant women; Hipsley used the term to describe intrinsic, non-digestible components of the plant cell wall, which included cellulose, hemicellulose, and lignin [3,4]. Later, Trowell and colleagues used the term dietary fibre to describe the remains of plant components resistant to hydrolysis by human alimentary enzymes, which included cellulose, hemicellulose, lignin, and associated minor substances, such as waxes, cutin, and suberin [17]. Trowell et al. then expanded this definition to include all plant components (i.e. the addition of pectins and gums) and not only those in the plant cell wall (i.e. oligosaccharides), which are resistant to digestion by human enzymes and display physiological effects of dietary fibre [18]. This definition was widely accepted during the 1980s and came about through the observation of lower rates of ‘Western’ diseases in those consuming traditional African diets, which were higher in dietary fibre than a typical Western diet, leading to the development of the dietary fibre hypothesis [19,20].

Over time, there have been numerous extensions/modifications to the definition of Trowell et al. It is now still widely recognised that dietary fibre must be resistant to digestion/absorption in the small intestine, with an additional recognition that it must be completely/partially fermented in the large intestine. Furthermore, definitions now include non-digestible carbohydrates which are analogous to those found in plants as dietary fibre (i.e. synthetic or extracted versions). Many definitions include a list of beneficial physiological effects, of which at least one must be exhibited to enable extracted/synthetic fibres to be classified as dietary fibre. Such effects include laxation, reduction in blood cholesterol, and attenuation of blood glucose response [4,16].

From the 1980s until 1999, the UK was traditionally the only country to measure dietary fibre using the NSP/Englyst method, which did not include oligosaccharides, resistant starch, lignin or extracted/synthetic fibre within its definition. The UK has since adopted the Codex Alimentarius definition in its full form, which was published in 2009, and is also accepted in its entirety by the EU and numerous other countries. The Codex definition gives the optional inclusion of oligosaccharides as dietary fibre and the decision of whether to include oligosaccharides within definitions is left to the discretion of authorities/regulatory bodies of each country. As mentioned earlier, inulin is accepted within the definition of dietary fibre by default due to being a natural non-digestible carbohydrate polymer. Both oligosaccharides and inulin are rapidly fermentable, with microbial effects that differ significantly from those of other dietary fibre components, such as NSP [21,22]. Thus, the inclusion of these LMW carbohydrates in the dietary fibre definition has various implications for consumers, especially those with FBDs.

2.2. Methods of measuring dietary fibre

The varying definitions of dietary fibre over time resulted in the need for different methods to quantify dietary fibre. The two most implemented and well-known techniques are the Englyst method and AOAC (Association of Official Analytical Chemists) methods. The Englyst method (also known as the NSP method) was developed in the 1980s by Englyst et al. and involves enzymatic-chemical extraction and fractionation of NSP [4]. This technique only considers NSP as dietary fibre and involves the division of NSP into cellulose and non-cellulosic material and the determination of constituent sugars by gas–liquid chromatography [23]. The Englyst method was used by the food industry and for nutrition and labelling in the UK until 1999 [24].

The AOAC method is an enzymatic-gravimetric approach used to determine total dietary fibre, not only NSP, by the isolation and weighing of dietary fibre residue [4]. This technique includes lignin and resistant starches, which are not NSP components. The first AOAC method (AOAC 985.29) was established around the year 2000 following the development of the Prosky total dietary fibre method, which became the official method in numerous countries, helping to harmonise free trade [24]. This technique, however, does not measure oligosaccharides and only partially measures resistant starch [25]. Thus, due to the inclusion of oligosaccharides within many worldwide definitions, the AOAC 2009.01 method was designed to measure dietary fibre as a whole (soluble and insoluble polysaccharides, lignin, resistant starch, and oligosaccharides), but cannot measure each component separately [25]. The AOAC 2009.01 method is recommended by Codex to quantify dietary fibre [26] and, in 2015, the Scientific Advisory Committee on Nutrition (SACN) suggested that the UK adopted this method to become aligned with most other nations [27].

Later, the AOAC 2011.25 method was developed to quantify insoluble and soluble fibre individually, which can also measure oligosaccharides separately [24]. This method is considered most reflective of the current Codex definition [28], but is only used when components are needed to be identified individually, which is not required for food labelling.

There are inconsistencies in methods used, however, which may cause great confusion. The Englyst method is still used in food composition tables and food intake assessments in the UK; more recent food composition tables, released in 2014, include dietary fibre values for both Englyst (NSP) and AOAC [24]. The AOAC method, understandably, gives higher values for fibre for most foods compared with the Englyst method. For example, the recommended daily intake of dietary fibre (30 g per day) in the UK is set using AOAC methods; the previous recommendation was set using the NSP/Englyst method, thus, giving a much lower value of 24 g per day [27].

2.3. Categories of dietary fibre

Dietary fibre is a form of carbohydrate, naturally occurring in all plant foods. Carbohydrates are classified according to their degree of polymerisation (DP) (number of molecules) [29,30], and exist in two varieties: digestible and non-digestible [31]. Monosaccharides and disaccharides are simple sugars, with a DP of 1–2, which are digestible by human alimentary enzymes and are, therefore, not classed as dietary fibre. Non-digestible carbohydrates, classed as dietary fibre or complex carbohydrates, can be split into two categories: short-chain and long-chain carbohydrates.

Short-chain carbohydrates include the oligosaccharides, which generally have a DP of 3–9 and are considered LMW dietary fibre; inulin is an exception to this and is also considered LMW dietary fibre, even with a DP of up to 60 [6–8,32]. Long-chain carbohydrates include the polysaccharides, which generally have a DP of ≥10, which in some cases can be up to a DP of 15,000 [33,34], and are referred to as high molecular weight (HMW) dietary fibre. NSP and resistant starch are the main two categories of HMW dietary fibre polysaccharides. NSP originate in the plant cell wall and exist as cellulose, hemicellulose, pectin, gums, and mucilages [28], whereas, oligosaccharides are plant energy reserves and do not originate in the plant cell wall [35]. It is worth noting that lignin is not a polysaccharide, but a complex random polymer associated with the plant cell wall, but is still considered as dietary fibre as it resists digestion in the intestine [4]. A visual representation of the different types of dietary fibre according to molecular weight is shown in Fig. 1.

2.4. Functional properties of dietary fibre

The effect that dietary fibre has in the colon, and its subsequent impact on health, depends on its solubility, fermentability, viscosity, and gel-forming ability, which varies between fibre types [36]. For many years, dietary fibre has been divided based on its solubility [4,28]; for example, oligosaccharides were previously excluded from definitions because of their solubility in 80% ethanol [37]. The classification of dietary fibre based on its solubility is perhaps unhelpful for predicting its physiological effect, as both soluble and insoluble fibre types can confer similar health benefits, but via different mechanisms, and many natural foods contain both soluble and insoluble fibre [28]. Thus, this classification has been recommended to be phased out by the Food and Agriculture Organization (FAO) and the World Health Organization (WHO) [38]. Oligosaccharides are now included within dietary fibre definitions based on their non-digestibility.

Insoluble, non-viscous fibre (such as wheat bran) can induce a laxative effect via mechanical stimulation of mucous secretion, but only if the particles are large or coarse [39,40]. Soluble, viscous fibre (such as psyllium) has a high water-holding capacity and turns to gel during digestion; viscosity relates to the ability of a fibre to thicken when hydrated [4,28]. The increased water content and bulk added to stools caused by these fibre types encourages laxation [40]. In fact, psyllium has the ability to normalise stools, i.e. softens hard stool in constipation, firms liquid/loose stool in diarrhoea, and normalises stool form/reduces symptoms in irritable bowel syndrome (IBS) [41]. Additionally, soluble, viscous fibres have been linked to the lowering of both serum total and low-density lipoprotein (LDL) cholesterol levels [1], therefore reducing the risk of cardiovascular disease. One of the mechanisms by which this occurs is due to the prevention of bile salt reabsorption from the small intestine [42].

It is worth noting that the above functional properties are characteristic of HMW dietary fibre, such as NSP. However, the role of soluble, but rapidly fermentable, fibres (i.e. non-digestible oligosaccharides and inulin) is somewhat different to other fibre types. These LMW dietary fibre types are fermented by gut bacteria in the proximal colon, producing short-chain fatty acids (SCFAs) and gases [43]. SCFAs play an important role in gut motility, modulation of the immune system, gut barrier integrity, appetite regulation, and gastrointestinal (GI) homeostasis [28]. LMW dietary fibre is known to selectively promote the growth and/or activity of beneficial bacteria in the colon, especially *Lactobacilli* and *Bifidobacteria* [44], potentially benefiting the health of the host, and

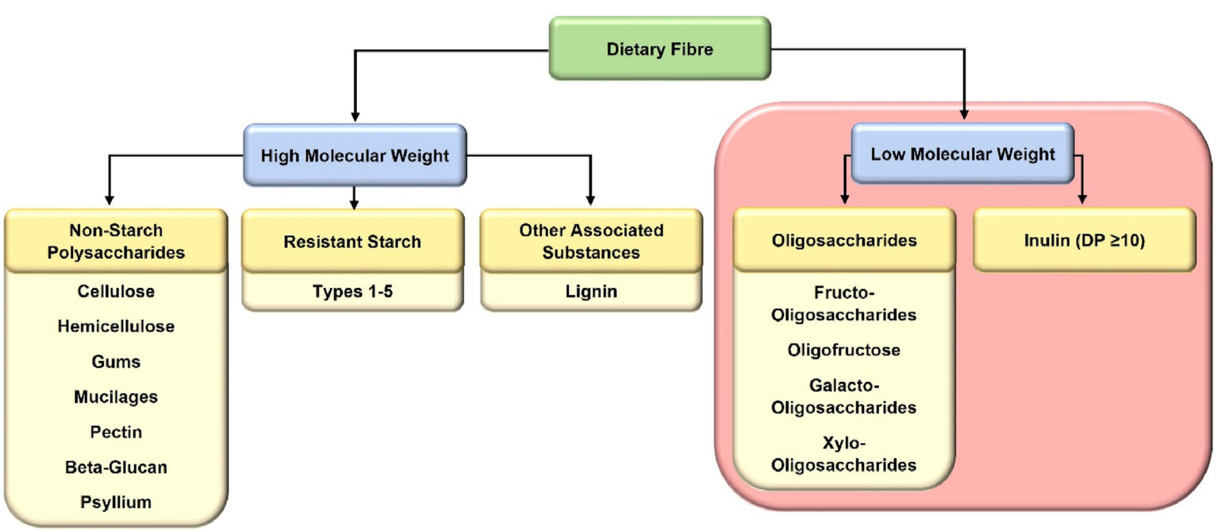

Fig. 1. A visual representation of the different types of dietary fibre according to molecular weight. Non-starch polysaccharides are high molecular weight, non-digestible carbohydrates and make up the bulk of dietary fibre intake in a European diet; they are present in high amounts in wholegrains, fruits, and vegetables and are known for their positive effects on health. Oligosaccharides and inulin are low molecular weight, non-digestible carbohydrates and are implicated in symptom induction in those with functional bowel disorders. Thus, the removal of oligosaccharides and inulin from the Codex Alimentarius definition of dietary fibre may be warranted. Please note: inulin with a degree of polymerisation (DP) of <10 is often referred to as fructo-oligosaccharides and oligofructose, and lists of components shown above are not exhaustive.

enabling their classification as 'prebiotics' [45]. Despite the prebiotic ability of oligosaccharides and inulin, a major side effect of their consumption is the high gas production caused by their rapid fermentation in the proximal colon. Whilst gas production occurs in all individuals, those with FBDs commonly experience flatulence and abdominal distention/bloating, resulting in abdominal pain/discomfort due to the presence of visceral hypersensitivity [46–48]. Additionally, it is worth mentioning that SCFAs are also end products of fermentable HMW dietary fibre, but fermentation occurs at a slower rate and is not concentrated in the proximal colon [30,49].

It has been suggested that the only mechanisms by which dietary fibre can cause a laxative effect are either through mechanical stimulation of the gut mucosa by insoluble fibre or the gel-forming ability of a soluble fibre [40]. However, soluble, rapidly fermentable fibres (i.e. oligosaccharides and inulin) do not possess either of these abilities and findings regarding the laxative effect of LMW dietary fibre are mixed. Whilst those with normal bowel function may not benefit from oligosaccharide supplementation, in terms of intestinal transit time or stool bulk/laxation [50], supplementation of oligosaccharides in those with low defecation frequency or constipation may aid laxation [51,52]. The effect on laxation witnessed from fermentable fibre is potentially due to increased microbial biomass, caused by fermentation by colonic bacteria, which contributes to stool bulk [43]; however, this effect may be insignificant compared with non-fermentable fibres [28]. The functional properties of different fibres have been reviewed extensively by So et al. [30].

3. Definitions and labelling regulations of dietary fibre

3.1. Codex Alimentarius definition of dietary fibre

Codex Alimentarius refers to a set of internationally recognised standards, guidelines, and recommendations, which was published by WHO and FAO in 1963 [53]. The Codex definition for dietary fibre is used for analytical methods, food labelling, setting of nutrient reference values, and health claims by many countries, including the UK, US, and those within the EU [20]. The definition follows the basis of previous definitions (i.e. all non-digestible carbohydrates, not only those in the plant cell wall) but recognises that there are three categories of dietary fibre: those naturally occurring in food, those obtained from raw material using enzymatic/chemical processes, and those that are synthetic [5]. Additionally, lignin is a complex random polymer associated with the plant cell wall, which resists digestion in the intestine; it is detailed in Footnote 1 of the Codex definition that lignin is included as dietary fibre if derived from plant origin. The full definition is shown in Table 1. Carbohydrates which are not intrinsic in food must be able to demonstrate a beneficial physiological effect to health, however, such beneficial effects are not specified and are left open to interpretation by competent authorities of each country [54]. The previous Codex definition, published in 2004, provided a list of beneficial effects to health, which were required to be met by even intrinsic fibre, but this was removed to simplify the definition [54] (Table 2).

Footnote 2 of the current Codex definition of dietary fibre is of high importance regarding the focus of this review. Within this Footnote, national authorities are given the option whether to include oligosaccharides (DP 3–9) within their definition of dietary fibre (Table 1), whereas the previous Codex definition included oligosaccharides within the main body of the definition (Table 2). The current Codex definition, with the inclusion of Footnote 1 (lignin) and Footnote 2 (oligosaccharides), has been accepted by the EU, UK, and US and many other countries, such as Canada, Australia, New Zealand, China, Japan, and Korea [24,55]. Chile accepts the Codex definition and inclusion of oligosaccharides for labelling purposes, but not for health claims, while South Africa does not accept the inclusion of oligosaccharides, along with countries which do not have a local regulatory definition [24]. For many other countries, it is unknown which definition they implement or whether they consider oligosaccharides as dietary fibre. Inulin is included within the main body of the current Codex definition of dietary fibre, due to it being a natural non-digestible polymer with a DP of ≥10, and is therefore accepted by default by all countries implementing this definition.

3.2. Regulatory body definitions of dietary fibre

Countries accepting the Codex definition in its entirety also have their own aligned definitions, established by their relevant regulatory body. Definitions involve slight variations in wording compared with the Codex definition, but many follow a similar basis (i.e. inclusion of oligosaccharides, inclusion of lignin if of plant origin, and the need for extracted/synthetic fibre to demonstrate a benefit to health) (examples of definitions are shown in Table 3). The EU and UK implement the European Commission (EC) definition of dietary fibre for food labelling purposes [58], which follows a very similar structure to the Codex definition, and the European Food Safety Authority (EFSA) definition for dietary reference values (DRVs) for dietary fibre [59].

The US Food and Drug Administration (FDA) accepted the Codex definition in 2016 for regulatory purposes, and currently implements the Institute of Medicine (IOM) definition as its own definition for dietary fibre [60]. The IOM distinguishes between fibre that is intrinsic in foods, which is termed 'dietary fibre', and fibre which is synthetic/extracted, termed 'functional fibre' (previously referred to as 'added fibre'). Within this definition, 'dietary fibre' and 'functional fibre' added together are referred to as 'total fibre', but functional fibre which has demonstrated a beneficial effect to health can be considered as dietary fibre on food labelling [24]. Canada adopts the Health Canada definition, which was reviewed following the development of the IOM and Codex definitions, and is now more aligned with both, but uses the term 'novel fibres' for extracted or synthetic fibre [61].

Table 1
The current Codex Alimentarius (2009) definition of dietary fibre [56], which includes the option to include oligosaccharides (degree of polymerisation [DP] 3–9) within Footnote 2 (shown in bold).

Dietary fibre means carbohydrate polymers1 with 10 or more monomeric units2, which are not hydrolysed by the endogenous enzymes in the small intestine of humans and belong to the following categories:
1. Edible carbohydrate polymers naturally occurring in the food as consumed.
2. Carbohydrate polymers, which have been obtained from raw material by physical, enzymatic or chemical means and which have been shown to have a physiological effect of benefit to health as demonstrated by generally accepted scientific evidence to competent authorities.
3. Synthetic carbohydrate polymers, which have been shown to have a physiological effect of benefit to health as demonstrated by generally accepted scientific evidence to competent authorities.
Footnote 1: When derived from a plant origin, dietary fibre may include fractions of lignin and/or other compounds associated with polysaccharides in the plant cell walls. These compounds may also be measured by certain analytical method(s) for dietary fibre.
Footnote 2: Decision on whether to include ***carbohydrates of 3 to 9 monomeric units*** *should be left up to national authorities.*

Table 2
The previous Codex Alimentarius (2004) definition of dietary fibre [57], which includes oligosaccharides (degree of polymerisation [DP] ≥3) in the main body of the definition (shown in bold).

Dietary fibre consists either of:
- Edible, naturally occurring in the food as consumed, non-digestible material composed of **carbohydrate polymers with a degree of polymerisation (DP) not lower than 3**, or of
- **Carbohydrate polymers (DP ≥ 3)**, which have been obtained from food raw material by physical, enzymatic or chemical means, or of
- **Synthetic carbohydrate polymers (DP ≥ 3).**

Dietary fibre is neither digested nor absorbed in the small intestine and has at least one of the following properties:
- Increase stools bulk
- [Increase laxative properties]
- Stimulate colonic fermentation
- Reduce blood total and/or LDL cholesterol levels
- Reduce post-prandial blood glucose and/or insulin levels.

LDL = low-density lipoprotein.

Table 3
Examples of worldwide definitions of dietary fibre.

Organisation	Definition
European Commission (EC) [58]	'Fibre' means carbohydrate polymers with three or more monomeric units, which are neither digested nor absorbed in the human small intestine and belong to the following categories: - edible carbohydrate polymers naturally occurring in the food as consumed; - edible carbohydrate polymers which have been obtained from food raw material by physical, enzymatic or chemical means and which have a beneficial physiological effect demonstrated by generally accepted scientific evidence; - edible synthetic carbohydrate polymers which have a beneficial physiological effect demonstrated by generally accepted scientific evidence.
European Food Safety Authority (EFSA) [59]	Dietary fibre is defined as non-digestible carbohydrates plus lignin
Institute of Medicine (IOM) [60]	*Dietary fiber* consists of non-digestible carbohydrates and lignin that are intrinsic and intact in plants. *Functional fiber* consists of isolated, non-digestible carbohydrates that have beneficial physiological effects in humans. *Total fiber* is the sum of dietary fibre and added fiber
Health Canada [61]	*Dietary fibre consists of:* 1. Carbohydrates with a DP[1] of 3 or more that naturally occur in foods of plant origin and that are not digested and absorbed by the small intestine; and 2. Accepted novel fibres. *Novel fibres are ingredients manufactured to be sources of dietary fibre and consist of carbohydrates with a DP of 3 or more that are not digested and absorbed by the small intestine. They are synthetically produced or are obtained from natural sources which have no history of safe use as dietary fibre or which have been processed so as to modify the properties of the fibre contained therein. Accepted novel fibres have at least one physiological effect demonstrated by generally accepted scientific evidence.* [1]DP: degree of polymerization or number of saccharide units.
American Association of Cereal Chemists (AACC) [17]	Dietary fiber is the edible parts of plants or analogous carbohydrates that are resistant to digestion and absorption in the human small intestine with complete or partial fermentation in the large intestine. Dietary fiber includes polysaccharides, oligosaccharides, lignin, and associated plant substances. Dietary fibers promote beneficial physiological effects including laxation, and/or blood cholesterol attenuation, and/or blood glucose attenuation.
Food Standards Australia New Zealand (FSANZ) [63]	Dietary fibre means that fraction of the edible parts of plants or their extracts, or synthetic analogues, that are resistant to the digestion and absorption in the small intestine, usually with complete or partial fermentation in the large intestine. Dietary fibre includes polysaccharides, oligosaccharides (degree of polymerisation >2) and lignins, and promotes one or more of the following beneficial physiological effects: 1. Laxation 2. Reduction in blood cholesterol 3. Modulation of blood glucose

From the 1980s until 1999, the UK implemented the NSP/Englyst method/definition of dietary fibre, which included only components of the plant cell wall (did not include oligosaccharides, resistant starch, or lignin) and did not accept extracted/synthetic fibre as dietary fibre. This definition advocates dietary fibre in the form of NSP as it is an integral part of a balanced diet, naturally present in high amounts in fruit, vegetables, and wholegrains, with evidence suggesting it to have positive effects on health [62]. More recent definitions include fibre types which are not as abundant in the above foods and allow the use of extracted/synthetic fibre, which has unknown effects on health [62].

3.3. Dietary fibre labelling regulations

Although the UK departed from the EU on 31st January 2020, it has retained EU law in many instances, which applies to food labelling and nutrition and health claims. In terms of food labelling, there are mandatory nutrition guidelines for prepacked food, which must be displayed on packaging. These requirements exist under EU Regulation No. 1169/2011 on the provision of food information to consumers, which has been applied since December 2016 [64].

Whilst it is mandatory to display energy value, fat, saturated fat, carbohydrates, sugars, protein, and salt on food labelling in the EU/UK, it is not mandatory to display dietary fibre. Dietary fibre is considered a supplementary nutrient, along with monounsaturated fat, polyunsaturated fat, polyols, starch, and many vitamins/minerals, whereby it is optional to include them on food labelling [64]. If a nutrition or health claim is made relating to dietary fibre, it becomes a mandatory nutrient which must be displayed. Dietary fibre is not accounted for within total carbohydrate on labelling.

In the US, the FDA sets requirements for nutrition labelling, which is required by law by the Nutrition and Labeling Act of 1990 [65]. Unlike the EU/UK, it is mandatory to display dietary fibre on the food label (known as Nutrition Facts [NF] label) in the US, as well as calories, total fat, saturated fat, trans fat, cholesterol, sodium, total carbohydrate, total sugars, added sugars, protein, vitamin D, calcium, iron, and potassium [66]. Voluntary nutrients include monounsaturated fat, polyunsaturated fat, sugar alcohols (polyols), and many vitamins and minerals [66]. Dietary fibre is also included within the total carbohydrate in the US, unlike in the EU/UK [67]. Within the voluntary list, dietary fibre can also be displayed as soluble and insoluble fibre on the NF label.

4. LMW dietary fibre: oligosaccharides and inulin

Oligosaccharides are a group of short-chain carbohydrates, of which there are two naturally occurring forms: those which are digestible (α-glucans, primarily derived from starch, such as maltodextrin) and those which are non-digestible (non-α-glucans) [68]. As described earlier, non-digestible oligosaccharides (which have been/will be referred to simply as oligosaccharides for the purpose of this review) are soluble and highly fermentable and are included within the definition of dietary fibre in many countries. Oligosaccharides are considered LMW dietary fibre and exist naturally in many foods, most commonly as fructans and galacto-oligosaccharides (GOS), which are frequently consumed worldwide as part of a typical modern diet. Inulin is a type of fructan and can exist as both oligosaccharides and polysaccharides but is considered LMW dietary fibre, regardless of chain length [6–8]. Oligosaccharides and inulin can also be extracted/hydrolysed from natural sources or produced enzymatically using disaccharides or other substrates [44,69]. This enables their use as ingredients in many common foods and beverages for a variety of purposes, one of which is to increase fibre content of a food product.

4.1. Categories of oligosaccharides

4.1.1. Fructans

Fructans are present in wheat, barley, rye, onion, Brussels sprouts, cabbage, broccoli, chicory, and Jerusalem artichokes in a complex mixture of different chain lengths [70]. Fructans can be linear or branched and are polymers of fructose linked by either β-2,1 or β-2,6 bonds (or both) with a terminal α-linked glucose and exist as oligosaccharides (DP 3–9), including fructo-oligosaccharides (FOS) and oligofructose, or polysaccharides (DP $\geq$ 10–60), known as inulins [71,72]. The differences in glycosidic linkages separate the fructans into inulin-type fructans (β-2,1 linked, found in Jerusalem artichoke and chicory), levan-type fructans (β-2,6 linked, found in forage grasses/monocotyledons and bacteria), or graminan-type fructans (both β-2,1 and β-2,6 linked, found in cereals such as wheat and barley) [73,74]. Fructans have been shown in numerous studies to promote the growth of beneficial gut bacteria, such as *Bifidobacteria* and *Lactobacilli*, enabling their classification as a prebiotic [72].

Physical separation techniques can be used to obtain commercial inulin from Jerusalem artichoke and chicory roots in varying chain lengths [69]. During this process, inulin is extracted from the root using hot water diffusion and is then purified and dried, which allows native inulin to be obtained with chains ranging from DP 2–60 [32]. From native inulin, FOS can be obtained via hydrolysis, using an inulase enzyme, into chains ranging from DP 2–10, as can high-performance inulin by removing shorter-chain molecules, giving a chain length ranging from DP 11–60 [32]. Additionally, FOS can be synthesized from sucrose by transfructosylation, using β-fructofuranosidase, which links additional fructose monomers to the sucrose molecules [32].

4.1.1.1. Inulin. The average chain length of native inulin is a DP of 10–20 [75], but inulin can exist in chain lengths of DP 2–60 [32]. The existence of inulin in shorter chains (i.e. DP 3–9) allows its classification as an oligosaccharide, and may also be termed FOS or oligofructose, thus having potential to cause confusion when these terms are used interchangeably (it is worth noting that FOS and oligofructose can also exist as other fructans, not only inulin-type fructans). As explained previously, despite being present in foods in chain lengths of up to a DP of 60, inulin is considered LMW dietary fibre. Although inulin with a chain length of DP > 10 is not fermented as quickly as short-chain inulin [76,77], long-chain inulin is still rapidly fermented compared with HMW dietary fibre, such as NSP [21,22], therefore posing an issue to those with FBDs. Whilst it may make more sense to reserve the term "inulin" only for inulin with DP $\geq$ 10 (as demonstrated earlier in Fig. 1), inulin is sometimes included within the oligosaccharide category in existing literature, due to its existence as FOS and oligofructose, and is listed within the oligosaccharide group which is excluded as part of the low FODMAP diet [78].

4.1.2. Galacto-oligosaccharides

Naturally occurring GOS are referred to as α-GOS and are the plant energy reserves of legume seeds, such as lentils, chickpeas, kidney beans, and peas [35,69]. α-GOS consist of α-linked galactose, α-linked glucose, and a terminal β-linked fructose and exist mainly as raffinose, stachyose, and verbascose, which have different numbers of galactose units linked to sucrose by an α-1,6 bond [72,74]. GOS produced synthetically from lactose are referred to as β-GOS, due to the different linkages. GOS are also known for their prebiotic effects, however, β-GOS are more selective for specific bacteria, such as *Bifidobacteria*, than natural α-GOS [72]; this is because GOS are metabolised by bacteria which possess the β-galactosidase enzyme to digest them [79].

Like FOS, β-GOS can be obtained by extraction and hydrolysis or can be synthesized enzymatically. Commercially synthesized β-GOS are produced from lactose via transglycosylation reactions using β-galactosidases, which can be expensive to produce due to the enzyme cost [69]. α-GOS can be obtained by extraction from pulses; however, unlike FOS, there is no inulin equivalent (i.e. no long polymer) from which α-GOS can be obtained by hydrolysis, it is hard to extract from natural sources, and the demand for α-GOS is lower than β-GOS, due to their lessened prebiotic ability [69].

4.1.3. Other oligosaccharides

Less common dietary oligosaccharides include xylo-oligosaccharides (XOS) [80]. XOS are found in honey, bamboo shoots, milk, fruits and vegetables and consist of xylose molecules connected by β-1,4 linkages [80]. Like fructans and GOS, XOS can be manufactured commercially to allow their incorporation into food and drink products. Additionally, human milk oligosaccharides, found in human breast milk, have received great attention regarding infant immunity [81]. There are also potential commercial applications for bovine milk oligosaccharides [82].

4.2. LMW dietary fibre as food ingredients

4.2.1. Labelling of added LMW dietary fibre

The EU/UK has a list of extracted/synthetic fibres which have demonstrated a beneficial effect to health and are therefore accepted as dietary fibre. Of these, oligosaccharides such as FOS, GOS, and other resistant oligosaccharides, and inulin are accepted as dietary fibre, which can be added to foods and included as fibre on food labelling, if chosen to be displayed.

In the US, providing added fibre has demonstrated a beneficial physiological effect to health, both intrinsic and added fibre are included as dietary fibre on the NF label [24]. For non-digestible carbohydrates which have not proven to be beneficial to health, they cannot be classed as dietary fibre and therefore cannot be included as such on labelling, but are to be listed under the total carbohydrate number instead. There are 6 non-digestible carbohydrates in the US which do not meet the criteria for dietary fibre, and the oligosaccharide, XOS, is one of them, which is considered as dietary fibre in the EU/UK. Initially, oligosaccharides and inulin were not approved as added fibres in the US, but the list has now been expanded to include GOS, inulin-type fructans (FOS), and inulin [83].

4.2.2. Nutrition and health claims for LMW dietary fibre

Nutrition claims and nutrient content claims in the EU/UK and US, respectively, for products which are 'high fibre' or a 'source of fibre' can be applied when oligosaccharides and inulin are added to food products (if included on the list of accepted extracted/synthetic fibres of each country). These claims are registered by the EFSA on the EU Register in the EU and Northern Ireland and must be authorised by the EC. Claims are registered in the UK by the UK Nutrition and Health Claims Committee (UKNHCC) on the GB Nutrition and Health Claims (NHC) Register in England, Scotland, and Wales [53]. In the US, nutrient content claims are permitted by The Nutrition Labeling and Education Act of 1990 once authorised by the FDA [84].

A health claim is any claim which implies a relationship between a product and health and can be split into 3 different forms in the EU/UK, which must be supported by generally accepted scientific evidence [53]. Health claims can also be split into 3 different categories in the US, depending on the strength of the evidence supporting the claim; for claims with less credible scientific evidence, wording on food products must be tailored to reflect this [84]. Furthermore, structure and function claims can be used in the US which can be used with no preapproval by the FDA and wording does not need to be tailored to address the level of scientific evidence [84].

To date, the only authorised health claim in the EU/UK which can be applied to all non-digestible carbohydrates (i.e. dietary fibre) is for their ability to reduce post-prandial glycaemic response compared with that of sugar-containing foods or drinks [85]. For oligosaccharides and inulin, the only authorised health claim is for native chicory inulin regarding its contribution to normal bowel function by increasing stool frequency [86]. This claim only applies to a daily intake of at least 12 g chicory inulin, with a mean DP $\geq$ 9. In the US, there are no health claims authorised for oligosaccharides or inulin.

4.2.3. LMW dietary fibre as prebiotics

A prebiotic was defined by the International Scientific Association for Probiotics and Prebiotics (ISAPP) in 2008 as a selectively fermented ingredient that results in specific changes in the composition and/or activity of the GI microbiota, thus conferring benefit(s) upon host health [87]. Whilst there is no universally accepted definition of a prebiotic, most definitions focus on improvement of human well-being [45].

Despite all oligosaccharides and inulin being prebiotics by nature, being able to label them as such on food/drink products is regarded as a health claim. There are no health claims permitted in the EU/UK regarding the ability of a prebiotic to modulate microbiota, as the EFSA concluded that there is not enough evidence to establish a cause-and-effect relationship [88]. The US also has a similar take on prebiotics; whilst it realises that their effect on gut microbiota is an emerging area of research, there is insufficient evidence to make recommendations [89]. In the EU/UK, however, a product can be labelled as a prebiotic if the authorised health claim for chicory inulin is used regarding its contribution to normal bowel function/increasing stool frequency. The labelling of foods as a prebiotic with the above health claim is becoming increasingly popular. This claim must be detailed on food labelling to justify its use as a prebiotic, stating how much inulin is contained within the product and that 12 g is required to demonstrate an effect.

4.2.4. LMW dietary fibre in functional foods

When nutrition/health claims are made in the EU/UK, the food product in question can be categorised as a functional food. Like dietary fibre, there is currently no universally accepted definition of a functional food, but the EU/UK considers a functional food to be any food consumed as part of a normal diet which affects specific functions of the body, improving health and well-being and/or reducing the risk of disease; it must not be a pill, capsule, or dietary supplement [90]. Thus, when oligosaccharides and inulin are added to products with an associated health or nutrition claim, this results in the creation of a functional food.

There is a large market for foods with increased fibre content, as many individuals fail to meet recommendations for dietary fibre, which range from 30 to 35 g/day for men and 25–32 g/day for women in most EU countries [24]. In 2021, The Food and Drink Federation launched an initiative in the UK named 'Action on Fibre' to boost consumer intake of fibre, whereby many well-known food companies have signed up with an aim to increase the fibre content of their products [91]. This demonstrates the vast amount of food products which may potentially include added LMW dietary fibre.

The use of oligosaccharides as sweeteners in food products to replace sugar is also common practice, as it provides a sweet taste without raising blood glucose levels [92]; this is especially the case for FOS, which have around 30% of the sweetness of sugar [69]. They can also be added to foods to replace fat, which is characteristic of inulin as it is able to mimic the texture of fat due to its microcrystalline gel and also provides no sweet taste [32,69]. In this case, foods may be considered functional if a nutrition claim was used relating to fibre content or reduced/low fat/sugar content. LMW dietary fibre may also be added to products which are not designed to benefit health, for example to improve texture, emulsification, stability, and shelf-life of confectionary, cakes and desserts [93]; thus, their use is not solely to produce a functional food. GOS are authorised as novel foods in the EU/UK as they were not widely consumed before 1997, and therefore have no history of consumption [94]. These oligosaccharides may be added to food and drink products such as milk, yoghurt, desserts, cereals, confectionary, infant formulas, and baby foods [94]. FOS and inulin have a history of use and have been consumed for many years, so are not considered novel foods, but are also added to many commonly consumed food products [32,95]. In the US, there is no official definition of a functional food and novel foods are not defined; instead, any new food ingredient is considered either as a food additive (requiring a pre-market approval by the FDA) or is generally recognized as safe (GRAS) for specific uses [96]. Many GRAS notices have been filed for oligosaccharides, such as FOS, GOS, and XOS, and for inulin, most of which have been accepted. Such notices display details for intended use in food products, which mostly include use as bulking agents, sugar replacers, humectants, fat replacers, and texture modifiers [97].

5. LMW dietary fibre in functional bowel disorders

The Rome IV criteria considers FBDs as a subset of functional gastrointestinal disorders, which include IBS, functional abdominal bloating/distention, functional constipation, functional diarrhoea, unspecified functional bowel disorder, and opioid-induced constipation [98]. FBDs are associated with reduced quality of life [13] and incur great healthcare costs [14]. The pooled global prevalence for FBDs was recently shown to be as high as 33.4% [12], evidently affecting a significant proportion of the population. The most well-studied of the FBDs is IBS and typical symptoms include abdominal pain, bloating, flatulence, constipation, diarrhoea, or a combination of both, depending on subtype. There is, however, great crossover between symptoms of all FBDs, and it is suggested that they instead exist as a continuum of disorders [98].

Food intolerance is strongly implicated in symptom induction in those with IBS and as many as 70% relate their symptoms to ingestion of certain foods, with 62% limiting or excluding certain foods from their diet [99]. Dietary therapy is, therefore, one of the main management methods for IBS symptoms. Frequently implemented dietary advice involves adherence to the low FODMAP diet; the main components removed during this diet are oligosaccharides and inulin, which will be discussed below. As IBS is the most well-studied of the FBDs, most research relating to dietary factors is focused in this area. However, due to the significant symptom overlap between disorders, research findings are likely highly applicable to all FBDs.

The low FODMAP diet was developed due to the association between consumption of fermentable short-chain carbohydrates and symptom induction in those with IBS. This approach features the removal of foods high in oligosaccharides (fructans and GOS), disaccharides (lactose), monosaccharides (fructose), and polyols (sorbitol and other sugar alcohols) for a period of 2–4 weeks, followed by a reintroduction and personalisation period [78]. It is worth noting that the oligosaccharide group of the low FODMAP diet includes inulin, of all chain lengths. During reintroduction, FODMAP-containing foods are used as challenges, which are consumed in increasing amounts over a 3-day period at the same time as monitoring symptoms, with the aim of being incorporated back into the diet for the long term [78]. All stages involve close monitoring by a specialist dietitian to ensure safety and efficacy. Examples of major sources of FODMAPs are shown in Fig. 2.

FODMAPs are proposed to increase small intestinal water and contribute to colonic gas production (via fermentation), which may cause bloating and abdominal pain in those with visceral hypersensitivity and, in the case of increased luminal water, may also contribute to diarrhoea [46–48]. Excessive gas production can also cause faster colonic transit in those with IBS-D, due to colonic sensitivity to increased intestinal volume [100]. The mechanisms by which FODMAPs cause symptoms are not fully understood. As well as luminal distention, caused by osmotic load and gas production (direct effect), FODMAPs may also worsen visceral hypersensitivity, inducing bloating, pain, and discomfort, via various peripheral factors (indirect effect), such as altered microbiota, increased intestinal permeability, and activated immune/inflammatory response [101].

Although associated with issues such as nutritional inadequacy, complexity, and restrictiveness [102], adherence to the low FODMAP diet results in a 50–80% response rate regarding reduction of IBS symptoms [103]. It has also shown similar [104] or greater [101,105] efficacy in reducing IBS symptoms, such as abdominal pain, bloating, and flatulence than first-line advice. Additionally, when compared with a typical Australian diet, lower overall GI symptoms were witnessed on a low FODMAP diet, as well as bloating, pain, and flatulence [106].

Malabsorption of lactose can occur in individuals who do not possess the lactase enzyme, and malabsorption of fructose can take place if eaten in excess (in excess of glucose or high amounts of free fructose) [107]. The absorption of polyols may be affected by varying molecular size and/or intestinal abnormalities [107]. Oligosaccharides and inulin, however, are not digested/absorbed in any individuals, due to lack of appropriate intestinal enzymes, such as β-fructofuranosidases and α-galactosidases for FOS and GOS, respectively (Atzler et al., 2021), so are far more likely to be implicated in symptom induction than other FODMAP components.

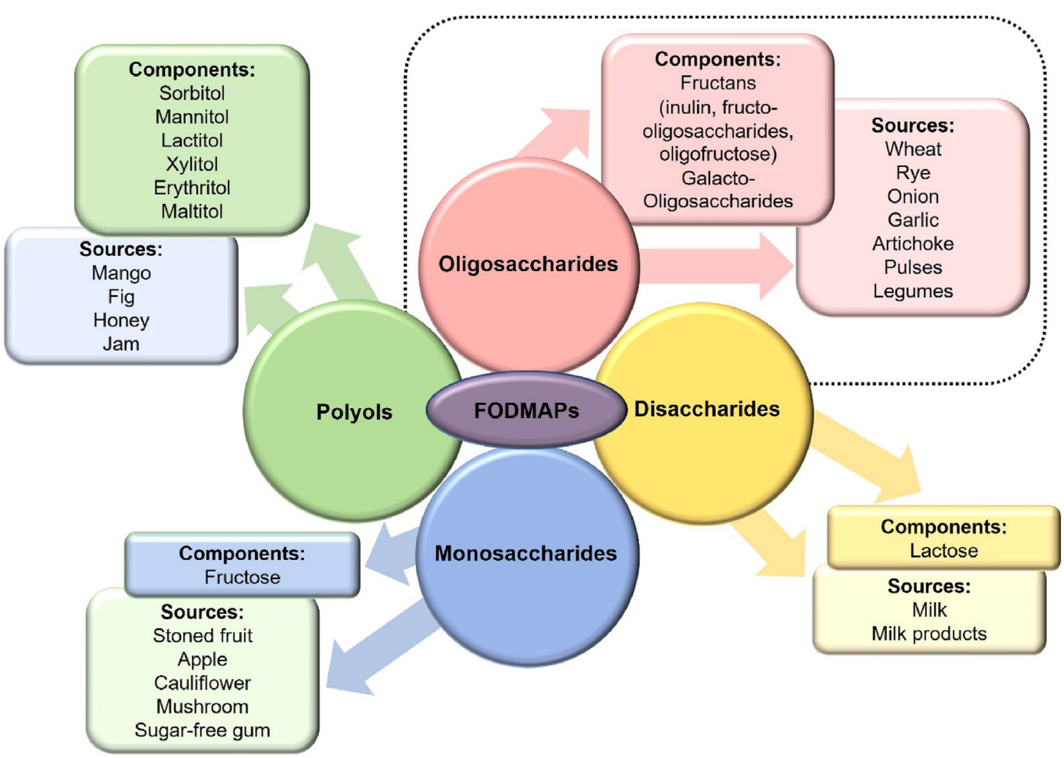

Fig. 2. The components of the low FODMAP (fermentable oligosaccharides, disaccharides, monosaccharides, and polyols) diet and respective sources, which must be excluded during the elimination phase of the low FODMAP diet. Oligosaccharides, including inulin, are the main components of the low FODMAP diet due to their presence in many commonly consumed foods. Figure produced using information from Whelan et al. [78].

Oligosaccharides and inulin are also the main components to be excluded of the low FODMAP diet as they are the most abundant LMW carbohydrates found in wheat-based grains, pasta, breads, breakfast cereals, pulses, legumes, onion, and garlic [70], which are consumed in high quantities in most modern diets. Thus, symptomatic improvement caused by FODMAP exclusion may be largely attributed to oligosaccharide and inulin removal in those with FBDs. For some individuals, it may be that foods containing oligosaccharides/inulin can never be reintroduced into the diet in the long term and must be permanently avoided to maintain symptom relief. The proportion of individuals suffering with FBDs worldwide is remarkable; thus, the impact of LMW non-digestible carbohydrates within the definition of dietary fibre, subsequent incorporation at high doses into commonly consumed food products, and lack of clarity on food labelling, is significant and may have a large impact on quality of life of these individuals.

6. Implications

6.1. Dietary fibre and lack of global harmonisation

The removal of oligosaccharides from the main body of the previous Codex definition for dietary fibre suggests that there is already controversy regarding their classification as dietary fibre. A prime reason for not removing them entirely from the current Codex definition, and instead making them optional, was to create global harmonisation; however, findings of this review suggest that this has not yet been achieved. Firstly, giving countries the option to include or exclude oligosaccharides from their regulatory dietary fibre definition essentially allows the use of two entirely different definitions. Secondly, lack of global harmonisation extends to food labelling regulations and nutrition/health claim legislation between the EU/UK and US (other countries), even when oligosaccharides are included within definitions. For instance, in the US it is mandatory to display dietary fibre on food labelling, and dietary fibre is also listed under total carbohydrate. In the EU/UK, however, dietary fibre is not mandatory (unless a nutrition claim is made regarding fibre content) nor is it included within total carbohydrate. This means that there are different energy values for fibre and carbohydrate values between countries; dietary fibre is calculated at 2 kcal/g in the EU/UK [108], but is calculated at 4 kcal/g in the US, as it is included under total carbohydrate.

Furthermore, although the US must display dietary fibre on labelling, non-digestible carbohydrates which do not meet the definition of dietary fibre (as they have not demonstrated a beneficial effect to health, e.g. the oligosaccharide, XOS) must be added under total carbohydrate; this means that oligosaccharides can be added to food products without being declared as dietary fibre on the label. The lists of accepted added fibres also differ between countries and, unlike the US, the EU/UK do accept XOS as dietary fibre, enabling it to be labelled as such, if included as a supplementary nutrient.

Finally, daily dietary fibre recommendations differ between countries, being 30 g per day in the EU/UK and 28 g per day in the US [24], which may affect interpretation of fibre content claims. To add to interpretation difficulties between countries, there are two forms of claim in the US which can be made without strong evidence to support the claim, proving somewhat more lenient than claims in the EU/UK. Lack of global harmonisation, which causes confusion for both researchers and consumers, is only part of the issue and does not consider the impact caused to those with FBDs when oligosaccharides are included within definitions of dietary fibre.

6.2. Harmful effects of LMW dietary fibre in FBDs

Although oligosaccharides are rarely studied in isolation from other FODMAPs, they are the main FODMAP component consumed in a typical Western diet, due to their presence in wheat products (such as bread, pasta, and breakfast cereals) and pulses/legumes [70]. Thus, they are largely responsible for symptom induction during a high FODMAP diet, and symptom relief during a low FODMAP diet, in those with FBDs. As mentioned earlier, the oligosaccharide group of the low FODMAP diet also includes inulin, of all chain lengths. The induction of symptoms following the consumption of LMW dietary fibre is proposed to be due to both direct and indirect effects, resulting from rapid bacterial fermentation in the proximal colon [30]. These effects will be discussed and are summarised in Fig. 3.

6.2.1. Direct effects of LMW dietary fibre in FBDs

Although healthy individuals may also experience increased gas production following the consumption of FODMAPs/oligosaccharides, it is postulated that the colonic visceral hypersensitivity to distention/luminal pressure is responsible for symptom induction (such as sensations of abdominal pain and discomfort) in those with FBDs. Visceral hypersensitivity is defined as low thresholds of stimuli perception arising from the gut and has been reported in up to 90% of those with IBS [109]. The presence of visceral hypersensitivity in those with FBDs has been shown in numerous studies; for example, separate doses of inulin and fructose both increased breath hydrogen in healthy individuals and in those with IBS, but those with IBS had higher symptom scores [48]. Similarly, higher levels of breath hydrogen were shown in both healthy individuals and those with IBS whilst following a high FODMAP diet, however, GI symptoms were significantly worse in those with IBS; healthy individuals experienced only increased flatus [46].

The increase in small intestinal water and excessive gas production caused by some FODMAPs may contribute to diarrhoea in those with IBS-D [100]. It is postulated, however, that oligosaccharides and inulin have no effect on small intestinal water. For example, inulin ingestion in healthy individuals and those with IBS resulted only in increased colonic volume and gas; the increase in intestinal water may be due to other FODMAPs, such as fructose, a monosaccharide [47,48]. Because of this, the low FODMAP diet has been most studied in those with IBS-D; evidence supporting its effectiveness in IBS-C or functional constipation is lacking. However, a novel approach, named the 5Ad Dietary Protocol, which focuses primarily on oligosaccharide exclusion, demonstrated significant improvements in all symptoms and subtypes of FBDs from baseline [110]. Although it can be difficult to attribute symptom reduction to oligosaccharide/inulin removal during such dietary interventions, a separate study demonstrated that muesli bars containing fructans induced significantly higher total symptom scores and bloating than muesli bars containing gluten in individuals with NCGS [111], demonstrating the strong role of oligosaccharides and inulin in inducing IBS-like symptoms.

6.2.2. Indirect effects of LMW dietary fibre in FBDs

As well as luminal distention, caused by osmotic load and gas production, FODMAPs may also worsen visceral hypersensitivity (inducing abdominal pain and discomfort) via various peripheral factors, such as altered microbiota, increased intestinal permeability, and activated immune/inflammatory response [101]. Numerous studies have demonstrated the interaction between, and aggravation of, these factors following consumption of a high FODMAP diet, which have been improved following a low FODMAP diet.

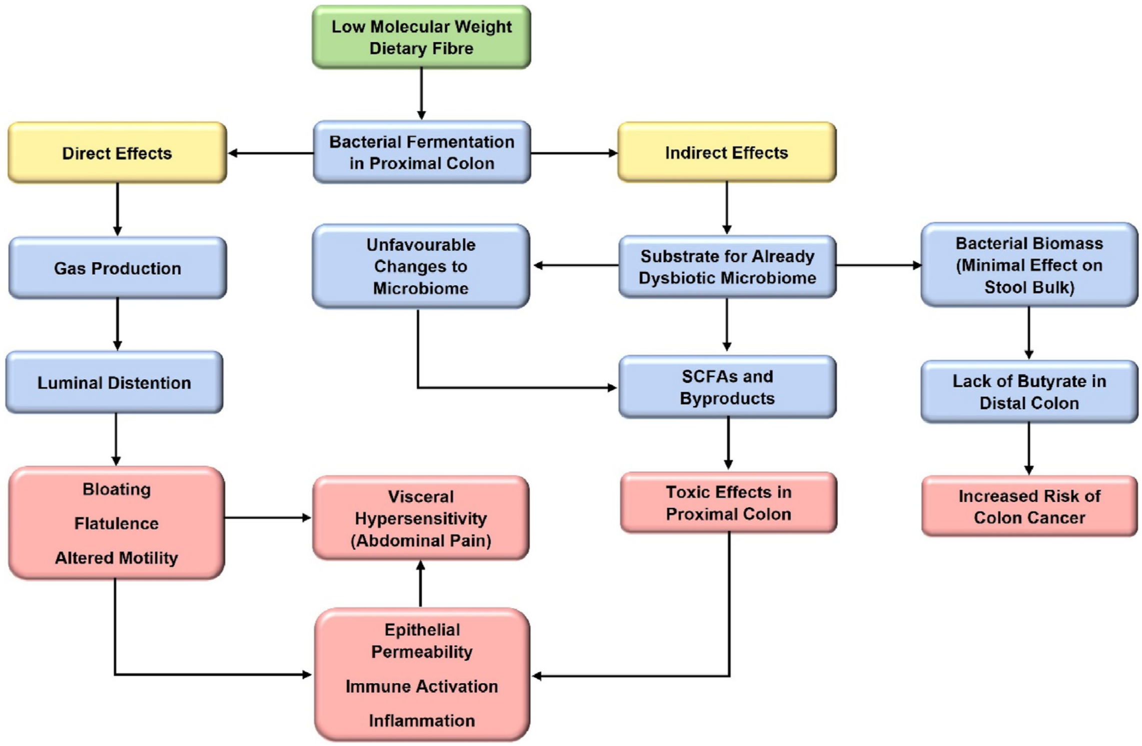

Fig. 3. The direct and indirect effects caused by low molecular weight dietary fibre (i.e. oligosaccharides and inulin) consumption in functional bowel disorders (FBDs). Visceral hypersensitivity is commonly experienced by those with FBDs, which gives sensations of abdominal pain and discomfort, and is heightened by luminal distention, altered microbiota, epithelial permeability, immune activation, and inflammation. Luminal distention can also cause bloating, flatulence, and altered motility.

Microbial dysbiosis is a common feature of those with FBDs, with reduced abundance of *Lactobacilli* and *Bifidobacteria* typically witnessed in those with IBS-D [112]. Those with IBS also tend to have an increased abundance of gas-producing bacteria, which is typical of those with constipation, and a reduced abundance of methanogenic archaea, which help to remove gas [100]. Dysbiosis can be caused by numerous factors, such as antibiotics, diet, host immune system, inflammation, and infective gastroenteritis [72]. Thus, due to the implication of dietary factors, it may be plausible that dysbiosis can in fact be caused by FODMAPs themselves due to their interaction with the microbiome. A high FODMAP diet was shown to cause microbial dysbiosis in rats after 2-week consumption, which led to mucosal inflammation and impaired gut permeability, likely contributing to visceral hypersensitivity [113]. Dysbiosis featured an overgrowth of Gram-negative bacteria, such as *Akkermansia muciniphilia*, which can contribute to impaired barrier function and inflammation [114]. This was associated with the presence of endotoxemia and lipopolysaccharides (LPS), shown in faecal samples, which are toxic and can also induce an inflammatory response [115].

Further to this, it appears that psychological stress may also cause harm to the microbiome/dysbiosis and, coupled with a high FODMAP diet, can worsen the above effects. The same researchers created a rat model of visceral hypersensitivity and mucosal inflammation by exposing rats to water-induced stress or restraint stress, to mimic psychological stress experienced by those with IBS. Rats exposed to restraint stress showed an increase in Gram-negative bacteria and an increase in LPS levels in the colon, as well as mucosal inflammation and gut permeability [113]. A 2-week low FODMAP diet, however, prevented the development of mucosal inflammation, impaired permeability and visceral hypersensitivity aggravated by stress. It also prevented the increase in Gram-negative bacteria and LPS, suggesting that a low FODMAP diet modulates the microbiota, likely because (unlike a high FODMP diet) it does not serve as nutrients for pro-inflammatory bacteria in the colon [113]. This has also been demonstrated in an IBS mouse model, whereby visceral hypersensitivity and intestinal inflammation were induced following exposure to water-induced stress, which was worsened by high doses of the oligosaccharide, FOS, administered for 2 weeks [116]. Inflammation was evidenced due to increased expression of pro-inflammatory cytokines (interleukin [IL]-23 and IL-1β) and increased mucosa mast cell counts.

Albeit, these studies were not carried out in humans, so results may not be transferrable, but inflammation has also been demonstrated in human subjects following consumption of a high FODMAP diet. Histamine, which is produced by mast cells during an immune response, was shown to be increased in the urine of individuals with IBS following a high FODMAP diet for 3 weeks [117]. This was proposed to be caused by either the signalling of SCFAs to mast cells or by mechanically induced-mast cell degranulation, caused by distention, and was also associated with significantly more days of pain compared with baseline [117]. Elsewhere, inflammation has also been demonstrated in response to a high FODMAP diet, which was subsequently reduced during a low FODMAP diet in those with IBS-D (levels of pro-inflammatory cytokines IL-6 and IL-8 were reduced), in addition to a significant reduction in all symptoms [118]. Interestingly, SCFAs and certain bacteria associated with anti-inflammatory effects were reduced during the low FODMAP diet, despite a reduced inflammatory response, suggesting the role of other potential mechanisms.

Furthermore, altered microbiota, and subsequent epithelial damage, can cause harm to enteroendocrine cells, thereby affecting many factors including gut motility, visceral hypersensitivity, and inflammation [119]. As such, densities of enteroendocrine cells in both the small and large intestine in those with IBS have been shown to be far lower than in healthy controls [120,121], suggesting the existence of altered microbiota and epithelial damage in these individuals. After a reduction in FODMAP intake, densities of enteroendocrine cells significantly increased, implying that a low FODMAP diet may positively change the microbiota, subsequently restoring cell densities/reducing epithelial damage in those with IBS [122].

The above findings are unexpected considering the well-known prebiotic ability of oligosaccharides and inulin. Numerous studies have demonstrated the ability of LMW dietary fibre, to promote the growth of beneficial bacteria, such as *Bifidobacteria* and *Lactobacilli* in healthy individuals [123–125]. The significance of increasing the growth of beneficial bacteria is due to the SCFAs produced during fermentation and their associated positive effects on health. For example, Firmicutes, such as *Lactobacilli*, are the main butyrate producers; butyrate is the main fuel for colonocytes and is known to protect against colon cancer [126]. Increased production of butyrate can also increase intestinal cell surface area, thus promoting mineral absorption, such as calcium [127]. Additionally, *Bifidobacteria* produce acetate, lactate, and organic acids which can be converted into butyrate, B vitamins and antioxidants [128].

Due to the above-mentioned beneficial effects on health, there are concerns regarding oligosaccharide/inulin exclusion during adherence to a low FODMAP diet. Research in this area has produced mixed findings, however, with either reductions or no changes in beneficial bacteria shown. For example, although microbial composition was not measured, microbial diversity was unaffected in those following a low FODMAP diet [129]. Elsewhere, a low FODMAP diet led to increased *Actinobacteria* richness and diversity but decreased *Bifidobacteria* [117,118]. Additionally, relative abundance of *Aldercreutzia* (which can decrease gas formation) was higher during a low FODMAP diet [117]. In attempt to prevent microbial changes resulting from the low FODMAP diet, prebiotics have been co-administered, but were shown not to prevent the reduction of *Bifidobacteria* in one study [130] and to increase *Bifidobacteria* in another, whilst significantly worsening symptoms [118]. Evidently, the long-term effects of the low FODMAP diet on the microbiome are unknown, but reductions in beneficial bacteria appear to coincide with improved symptoms in those with IBS.

The recognition of oligosaccharides/inulin as prebiotics gives the association that they are beneficial to health. However, this may only be in individuals with a certain microbial composition; there is high inter-individual variability in terms of the microbiome, which may influence an individual's response to diet [131]. For example, in germ-free mice harbouring human-derived microbiome, the same dietary fibre consumed by different mice led to different metabolic outcomes [131]. The composition of the microbiome can have an impact on fermentation, as different bacteria preferentially metabolise different types of fibre [28]. This may explain the differences observed in the above study and may also explain why those with FBDs, who typically have a dysbiotic microbiome, respond to oligosaccharide consumption in a different manner to those with a more favourable microbial composition. It is also possible that oligosaccharides and inulin may increase the abundance of some harmful bacteria/metabolites, thereby exaggerating any abnormal signalling [117]. Although the exact mechanism is unknown, it is apparent that oligosaccharides and inulin interact with the microbiome of individuals with FBDs in some respect, inducing inflammation and abdominal symptoms in those with visceral hypersensitivity. These effects are likely a consequence of their rapid fermentation in the proximal colon, which does not occur with HMW dietary fibre [30].

6.3. LMW dietary fibre in food products

6.3.1. Quantities and safety of added LMW dietary fibre

Whilst the estimated daily consumption of inulin, FOS, and GOS in Westernised diets is in excess of 10 g [132], those following the low FODMAP diet are recommended to drastically reduce their oligosaccharide/inulin intake to <0.2–0.3 g per serving of individual food per sitting (or total FODMAP intake to 0.5 g per sitting), depending on which oligosaccharide- or inulin-containing foods are consumed [133]. It is advised that total FODMAP content should be around 2.5–3 g per day, including all FODMAP components, not only oligosaccharides (typical Western diet ranges from 15 to 30 g per day of total FODMAPs) [134]. Added oligosaccharides and inulin in food products are present in far higher amounts than those occurring in natural foods. With research demonstrating that up to 20 g of inulin and FOS is well tolerated in the general population [135] and that 3 servings of 12 g GOS can be tolerated per day [136], the levels at which LMW dietary fibre can be added to foods are high and could lead up to at least 20 g extra consumption per day [93]. Evidently, the classification of oligosaccharides and inulin as dietary fibre and subsequent incorporation into commonly consumed food products has a large impact on those with FBDs.

The estimations for tolerated levels of oligosaccharides and inulin are based on extracted/synthetic versions, of which the long-term safety and established safe-upper limits are unknown, with no warning on food products regarding how much can be consumed. Even the general population may experience symptoms after excessive consumption of oligosaccharides; for example, doses of >30 g FOS per day may induce excessive flatus, >40 g per day borborygmi and bloating, and >50 g per day abdominal cramps and diarrhoea [137]. The fact that extracted/synthetic fibre must demonstrate a health benefit in order to be classified as dietary fibre raises issues regarding its safety in comparison to intrinsic fibre and, if oligosaccharides and inulin cannot be consumed in such large amounts in natural foods, it may not be safe to have such high synthetic doses. Elsewhere, they have even been described as pharmacological agents [20].

Moreover, commercial oligosaccharides and inulin are associated with issues of lack of purity and may contain other components which reduce their health benefits, making wellness claims misleading. For instance, glucose, fructose and sucrose are naturally present in chicory inulin [32] and when producing FOS enzymatically [69]. A similar issue occurs with the production of β-GOS whereby glucose, galactose, and lactose are present [69]. Further enzymatic treatment is required to remove these sugars, which is expensive, making pure versions available only for analytical purposes [69]. To be used in food products as a novel food in the EU/UK, β-GOS must contain no more than 40% lactose, no more than 22% glucose [94]. Similar issues exist with FOS mixtures, which may have as little as 55% purity [69]. The presence of these sugars in commercial oligosaccharides means that they are not in fact low calorie, may raise blood glucose levels in some individuals, may have a reduced prebiotic effect, and can potentially be carcinogenic [69].

6.3.2. Labelling of LMW dietary fibre

Natural foods containing oligosaccharides and inulin are easy to identify (both visually and in the ingredients list of products), and subsequently avoid, by those excluding these non-digestible carbohydrates from their diet. In contrast, extracted/synthetic versions in food products are difficult to identify due to lack of clarity of labelling (i.e. no way of determining how much fibre is intrinsic and how much is added). This has been recognised elsewhere and was suggested that the labelling of dietary fibre could be in the form of ‘Fibre Ng per 100 g, of which Xg is supplemental’ [55], to provide more clarity to consumers. This would be of more use than the optional listing of dietary fibre in the US as soluble and insoluble subtypes which, as described earlier, is a poor indicator of physiological effect.

Additionally, whilst individuals following the low FODMAP diet are advised to avoid foods containing fructans and GOS, XOS are ignored due to beliefs that they are not commonly consumed [138]; in this case, individuals would not know to look for XOS on food labelling. The terminology used for oligosaccharides in the ingredients list may also be confusing to consumers, with inulin being listed, not only as inulin, but as chicory inulin, chicory extract, or chicory root fibre.

6.3.3. Extracted/isolated dietary fibre and functional foods

In terms of health effects, it is yet to be determined how comparable extracted/synthetic forms of dietary fibre are to fibre which is intrinsic in foods. Firstly, extracted/synthetic dietary fibre can be consumed in far higher amounts when incorporated into food products than when present naturally in the diet. This is partly because of the vast quantities added to products, but also because when natural, fibrous food is consumed, it is more satiating due to other components, such as the high-water holding capacity of fruit and vegetables and bulking ability of wholegrains, making it difficult to overconsume [37]. Additionally, naturally, high-fibre foods do not only contain one form of fibre, and also contain many other nutrients, such as antioxidants, vitamins, minerals, and phenolic compounds, known to benefit health [139].

Public health messages, reference intake values, and wellness claims in relation to dietary fibre have been established based on findings from epidemiological studies regarding the protective effects of wholegrains, fruits and vegetables against the development of non-communicable diseases; these are whole food groups rather than an isolated component [37]. Because of these associations, the term ‘dietary fibre’ has developed the connotation of being beneficial to health, regardless of its source. Thus, there is concern that individuals may strive to obtain their daily dietary fibre intake from functional food products claiming to be ‘high in fibre’ or a ‘source of fibre’, believing they are equivalent to naturally high-fibre foods; this results in avoidance of important nutrients contained within the food matrix.

To add to uncertainty in this area, the Codex definition requires added fibres to demonstrate a beneficial physiological effect to health, but does not provide a list of these effects, making it difficult to ascertain which effects are meaningful, to what extent they are required in order to provide benefit, and who is authorised to determine this [20].

6.4. LMW vs. HMW dietary fibre

Another prominent point is the contrast between HMW dietary fibre (i.e. polysaccharides, such as NSP) and LMW dietary fibre (i.e. oligosaccharides and inulin) regarding their effect in the bowel. As previously explained, the effect that dietary fibre has in the colon is determined by its functional properties [36]. LMW dietary fibre is soluble and highly fermentable, reaching the colon intact whereby it is fermented by colonic bacteria, producing SCFAs and gases. Thus, oligosaccharides and inulin are mostly associated with their microbial effects and, whilst they may contribute to stool bulk via increased microbial biomass in the stool, these effects are negligible compared with those of NSP [28].

In contrast to LMW dietary fibre, almost all forms of HMW dietary fibre contribute to stool bulk and transit time. NSP which have gel-forming ability and/or are viscous (and minimally fermented), such as arabinoxylan (form of hemicellulose, viscous) and cellulose (non-viscous), found in wheat and psyllium, have high water-holding capacity and, in the case of viscous psyllium, can increase small intestinal water [30]. Both mechanisms contribute to stool weight and a softened stool consistency. Non-viscous NSP, without gel-forming ability, such as wheat bran, can cause mechanical stimulation of fluid secretion if particles are large or coarse, increasing stool water and transit time [28,30]. Thus, the NSP content of a food determines its ability to increase stool bulk. It was demonstrated that stool weight increased by 127% with wheat bran and 69% with cabbage fibre [140]. Whilst both fibre types are fermentable, wheat bran also has particulate and water-holding abilities, as explained above, whereas cabbage fibre is predominantly fermentable, likely due to its higher oligosaccharide (fructan) to NSP ratio than wheat bran, which explains its reduced ability to increase stool weight compared with wheat bran.

Furthermore, around 90% of plant cell-wall material comprises NSP, which makes up the bulk of dietary fibre present in wholegrains, fruits and vegetables [141] and may, in part, be responsible for the positive effects on health demonstrated by these food groups [62]. Thus, public health messages advocating a diet rich in wholegrains, fruits, and vegetables are essentially promoting a diet which is high in NSP. In fact, HMW dietary fibre, including NSP (cellulose, hemicellulose, pectin, beta-glucans, and gums), resistant starch and lignin represents around three quarters of total fibre intake in a European diet, whereas LMW dietary fibre (oligosaccharides and inulin) represents less than one quarter [30] (Fig. 4). This demonstrates that the contribution of oligosaccharides and inulin to dietary fibre intake is insignificant in comparison to that of HMW dietary fibre.

The detrimental effects caused by LMW dietary fibre in those with FBDs have already been discussed; however, there are further harmful effects caused by oligosaccharide and inulin fermentation which can affect even the general population. Fermentation which occurs in the distal colon helps to protect against colorectal cancer, due to the ability of the SCFA, butyrate, to slow the rate of cancer cell proliferation and induce differentiation of mucosal cells [126]. LMW dietary fibre, however, is fermented rapidly in the proximal colon and SCFAs are quickly absorbed, and therefore do not contribute butyrate to the distal colon [126]. Additionally, the subsequent production of SCFAs and lactic acid in the proximal colon may also produce toxic effects, which can lead to impaired barrier function/epithelial injury, mucosal inflammation, and increased visceral hypersensitivity (Fig. 3) [30,142].

Moving fermentation to the distal colon via the consumption of different fibre types simultaneously is one method to achieve protective health benefits from readily fermentable fibre [143,144]. It is proposed that consumption of a rapidly fermentable fibre, which is fermented primarily in the proximal colon, with a more slowly fermentable fibre would essentially fill up/satiate the proximal colon, leading to the remaining, slowly fermentable fibre reaching the distal colon [144]. The further addition of a fibre which speeds up transit and is minimally fermented may prove even more effective [30]. Research relating fibre coadministration involving oligosaccharides/inulin is lacking and, aside from the protective effects of pushing fermentation distally, there are mixed views regarding whether symptoms produced from highly fermentable fibres would be reduced. For example, some speculate that bloating and discomfort would still be induced [30] and others believe that dysbiosis would be corrected, and stool form and transit time would be normalised [28].

7. Recommendations

7.1. Removal of LMW carbohydrates from codex definition of dietary fibre

Aside from attempts to achieve global harmonisation, the decision to include oligosaccharides (DP 3–9) as dietary fibre was due

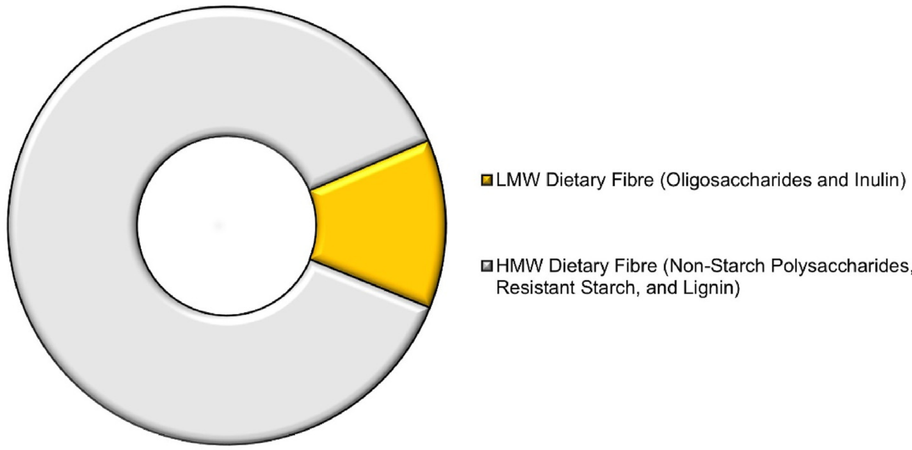

Fig. 4. Percentage contribution of low molecular weight (LMW) dietary fibre (i.e. oligosaccharides and inulin) intake to average total fibre intake in a European diet compared with high molecular weight (HMW) dietary fibre. Non-starch polysaccharides, i.e. cellulose, beta-glucan, pectins, hemicelluloses and gums, make up around three quarters of total fibre intake and comprise the bulk of dietary fibre found in wholegrains, fruits and vegetables. Figure adapted from So et al. [30].

to the inability to distinguish them from some polysaccharides (DP $\geq$ 10) based on their solubility in 80% ethanol, as mentioned earlier. This technique was previously used for the NSP method of determining dietary fibre, which led to the exclusion of oligosaccharides from definitions [37]. An issue with this, however, is that polysaccharides with DP $\geq$ 10 can also be removed by the ethanol wash, depending on the branching or nature of constituent monosaccharides [5,54]. The cut-off point between dietary fibre with DP 3–9 and DP $\geq$ 10 has therefore been deemed meaningless and non-digestible carbohydrates have, instead, been considered as part of a continuous spectrum, with no clear cut-off point at any length [54]. Based on this theory, it was suggested that there would be no reason to class polysaccharides as dietary fibre and not oligosaccharides. It has also been questioned how oligosaccharides would be categorised if they were considered neither a digestible carbohydrate nor a non-digestible carbohydrate [5]. Thus, oligosaccharides are included within dietary fibre definitions based on their physiological effects (i.e. non-digestibility), rather than their solubility. However, it does not make sense class both oligosaccharides and polysaccharides as dietary fibre, based on their non-digestibility, but to separate oligosaccharides from disaccharides which, in some cases, also share comparable physiological effects. For example, carbohydrates with DP < 3, such as lactulose and polyols, show similar prebiotic effects to oligosaccharides/inulin, yet are not classed as dietary fibre [37].

Overall, it seems illogical for LMW and HMW non-digestible carbohydrates to be placed in the same category, as dietary fibre, when both display different functional properties and subsequent effects in the bowel; NSP, unlike oligosaccharides and inulin, are associated with more traditional properties of dietary fibre, relating to bowel function, and not for microbial/prebiotic effects. Therefore, instead of non-digestibility, it may make more sense to consider molecular weight as the crucial factor in determining carbohydrate classification and, subsequently, its place as dietary fibre. Technically, the lower the DP of a non-digestible carbohydrate, the lower its molecular weight and the more rapid its fermentability. Based on this, non-digestible carbohydrates are generally split into those which are LMW (i.e. oligosaccharides with DP 3–9) and those which are HMW (i.e. polysaccharides with DP $\geq$ 10), as explained earlier. This rule, however, does not apply to inulin which can have a DP of 60, yet is considered a LMW carbohydrate and is rapidly fermented. It may make more sense, therefore, to amend the DP cut-off point for HMW dietary fibre and to remove LMW non-digestible carbohydrates entirely from the definition of dietary fibre. A cut-off point of DP $\geq$ 100 for HMW dietary fibre may be a good starting point, as HMW non-digestible carbohydrates typically have a DP well above 10. For example, hemicellulose has a DP of 100–200 and cellulose has a DP of 9000–10000 (can be up to DP 15000 in some instances) [33,34], which are the most abundant NSP found in plants [145], and beta-glucan, another common form of NSP, has DP 1200–1850 [145]. Perhaps even more practical than molecular weight would be utilising the speed of fermentation as the crucial factor in determining carbohydrate classification, whereby only slowly fermented carbohydrates are considered as dietary fibre. Either method suggested above would feature the removal of LMW non-digestible carbohydrates from the Codex definition of dietary fibre (Fig. 5), consequently benefiting those with FBDs.

7.2. LMW non-digestible carbohydrates as prebiotics or food additives

As explained earlier, the LMW non-digestible carbohydrates are mainly associated with their potential prebiotic effects; however, they cannot carry a claim directly related to their prebiotic ability in the EU/UK or US, as no cause-and-effect relationship has been established [146]. The need for prebiotics is indeed questionable; whilst research has shown their ability to simulate the growth of beneficial bacteria in healthy individuals, studies have been carried out using extracted/synthetic oligosaccharides and inulin as the effects of intrinsic versions cannot be studied in isolation from other components in the food matrix. Oligosaccharides and inulin are also proposed not to occur naturally in food at high enough doses to confer a prebiotic effect [80]. If such high doses cannot be achieved through food alone, it begs the question as to whether it is advisable to consume such high doses of extracted/synthetic prebiotics and why they are required in the first place; this is likely to be to counteract the detrimental effects of the Western diet caused to the microbiome [147], rather than being a necessity for health. Whilst, in some individuals, the consumption of prebiotics may help to reduce disease risk and improve health, they are not a quick fix or magic pill and there is no substitute for a healthy, balanced diet, containing wholegrains, fruits and vegetables.

This is not to say that oligosaccharides and inulin do not have a place as prebiotics, but perhaps should be classed separately as such and not as dietary fibre which, instead, is a necessity to health. The

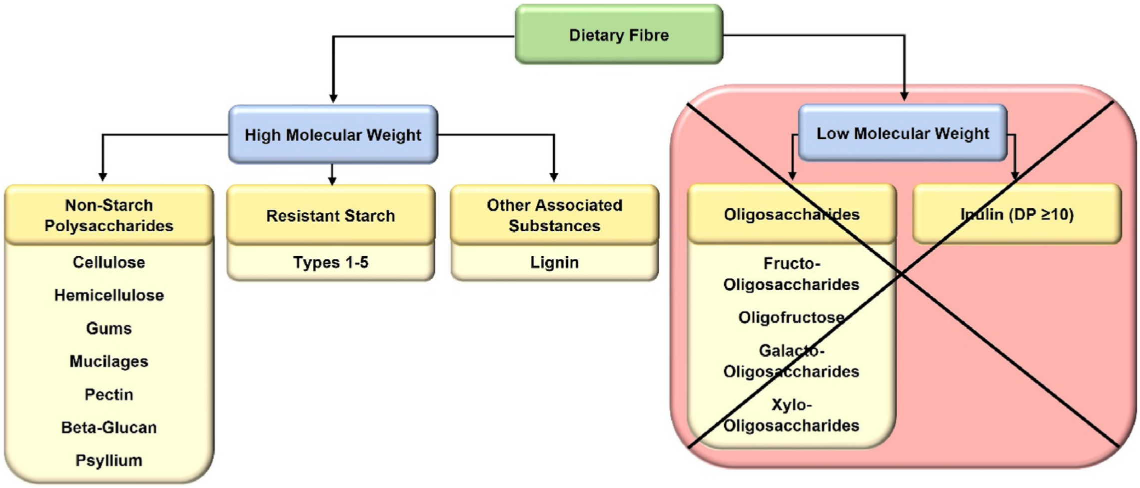

Fig. 5. Proposed removal of low molecular weight non-digestible carbohydrates (i.e. oligosaccharides and inulin) from the Codex definition of dietary fibre, to consider only high molecular weight non-digestible carbohydrates, i.e. non-starch polysaccharides (NSP), resistant starch, and other associated substances (such as lignin), as dietary fibre. The bulk of dietary fibre found in wholegrains, fruits and vegetables comprises NSP, and public health messages strongly advocate consumption of these food groups, due to their evidenced positive effects on health.

removal of LMW non-digestible carbohydrates from the Codex definition of dietary fibre and placement in their own category as prebiotics would enable them recognition for their microbial effects, rather than their minimal effect on bowel function. Oligosaccharides and inulin could then be readily avoided by those who did not benefit from their consumption, especially if labelling included wording such as 'with added oligosaccharides/inulin' and included a safe-upper limit. This method is already implemented when phytosterols/phytostanols (other non-dietary fibre plant components) are added to foods, based on their authorised health claim of lowering blood LDL cholesterol. Products containing these components must include the wording 'with added plant sterols/ plant stanols' and that consumption of more than 3 g per day should be avoided, which are both displayed in the same field of vision as the name of the product, providing great clarity to the consumer [148].

Another option would be to consider oligosaccharides and inulin as food additives, instead of dietary fibre or prebiotics, based on their properties as sweeteners, bulking agents, and humectants, for example. The name and function of each food additive must be clearly displayed on the ingredients list of food products in which they are contained [149]. This would prevent these LMW non-digestible carbohydrates from being marketed to those with FBDs using potential health claims which were originally established based on their effects on healthy individuals.

7.3. *Towards oligosaccharide-free products*

Methods to reduce oligosaccharide content of natural foods, such as soaking, cooking, germinating, and fermenting, have been implemented for many years to assist with the digestibility of common foods. The soaking or germination/sprouting of legumes can reduce α-GOS and antinutritional factor content [150,151], and cooking after soaking may lead to further decreases in α-GOS content [152]. Furthermore, fermentation during baking can degrade 40–80% of fructans, and may also remove ATIs, additives, and gluten [153]. Fermentation can also be used to reduce α-GOS levels and anti-nutritional factors in soybean, which is commonly carried out to produce soy sauce, miso paste, tempeh, and tofu [153]. These traditional methods could be utilised to produce oligosaccharide-free foods, which have potential to improve the quality of life for those with FBDs. There is already a large market for 'free-from' foods, such as gluten-free or lactose-free products, for those suffering with a related food allergy or intolerance.

8. Conclusion

Controversies regarding the classification of LWM non-digestible carbohydrates (i.e. oligosaccharides and inulin) as dietary fibre have been significantly substantiated by this review. The impact caused to those with FBDs is especially notable, due to the deleterious health effects caused by oligosaccharide and inulin consumption. Ultimately, the inclusion of LMW non-digestible carbohydrates within definitions has prevented dietary fibre from being a universally beneficial dietary component for all individuals.

Thus, following the basis of this review, it would be justified to remove LMW non-digestible carbohydrates entirely from the Codex definition of dietary fibre, with the aims of achieving a standardised approach between countries and a universally beneficial dietary component. In terms of global harmonisation, the removal of LMW non-digestible carbohydrates would appear more favourable than attempts to standardise food labelling and nutrition/health claim regulations between countries, as inconsistencies would remain regarding oligosaccharide inclusion within worldwide definitions.

Instead of classification as dietary fibre, oligosaccharides and inulin could be placed in their own category as prebiotics, recognised for their specific functional properties, or considered as food additives whereby they are not promoted for being beneficial to health. Finally, a potential market exists for oligosaccharide-free foods for those with FBDs, providing a further opportunity to improve the quality of life for these individuals.

Author contribution

PS: Conceptualization, Investigation, Writing – Original Draft, Writing - Reviewing & Editing, Visualization. **FI:** Conceptualization, Writing – Reviewing & Editing, Supervision.

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Declaration of competing interest

The authors declare no conflicts of interest.

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