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## Opinion paper

## Nutritional interest of dietary fiber and prebiotics in obesity: Lessons from the MyNewGut consortium



Nathalie M. Delzenne <sup>a, \*</sup>, Marta Olivares <sup>a</sup>, Audrey M. Neyrinck <sup>a</sup>, Martin Beaumont <sup>a</sup>, Louise Kjølbæk <sup>b</sup>, Thomas Meinert Larsen <sup>b</sup>, Alfonso Benítez-Páez <sup>c</sup>, Marina Romani-Pérez <sup>c</sup>, Vicenta Garcia-Campayo <sup>d</sup>, Douwina Bosscher <sup>e</sup>, Yolanda Sanz <sup>c</sup>, Jan-Willem van der Kamp <sup>f</sup>

<sup>a</sup> Metabolism and Nutrition Research Group, Louvain Drug Research Institute, Université catholique de Louvain, Brussels, Belgium

<sup>b</sup> Department of Nutrition, Exercise and Sports, Faculty of Science, University of Copenhagen, Rolighedsvej 30, 1958, Frederiksberg C, Denmark

<sup>c</sup> Microbial Ecology, Nutrition & Health Research Unit, Institute of Agrochemistry and Food Technology, Spanish National Research Council (IATA-CSIC), Valencia, Spain

<sup>d</sup> Cargill Inc., R&D Centre, Plymouth, Minneapolis, MN, USA

<sup>e</sup> Cargill R&D Centre Europe, Vilvoorde, Belgium

<sup>f</sup> Netherlands Organisation for Applied Scientific Research TNO, Zeist, the Netherlands

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## SUMMARY

The aim of EU project MyNewGut is to contribute to future public health-related recommendations supported by new insight in gut microbiome and nutrition-host relationship. In this Opinion Paper, we first revisit the concept of dietary fiber, taking into account their interaction with the gut microbiota. This paper also summarizes the main effects of dietary fibers with prebiotic properties in intervention studies in humans, with a particular emphasis on the effects of arabinoxylans and arabinoxylo-oligosaccharides on metabolic alterations associated with obesity. Based on the existing state of the art and future development, we elaborate the steps required to propose dietary guidelines related to dietary fibers, taking into account their interaction with the gut microbiota.

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## 1. Introduction

One of the goals of the MyNewGut consortium is to generate scientific knowledge that helps to take into account microbiota-nutrients interactions to establish dietary recommendations as part of healthy lifestyles. Within this framework, the MyNewGut consortium has recently worked on a set of Opinion Papers founded on the project results and the latest advances in the field [1]. Regarding the role of dietary fiber (DF), recent reviews outline the benefits of ancestral diets and high fiber diets to maintain a rich and diverse gut microbiome and related health benefits [2]. In light of those data, some studies propose that DF intake would at least reach 50 g/day, whereas the current recommendations are around 30 g per day in the adult [3]. Despite the common characteristic of

being non-digestible in the human small intestine, the DF is widely different in composition, structure and the way they are feeding the bacteria harboring the gut microbiota. Therefore, this Opinion Paper focuses on the results of studies performed with prebiotic fibers studied in the MyNewGut project –namely arabinoxylo-oligosaccharides (AXOS)- and outlines recommendations for an in-depth understanding of gut microbiota-fiber interactions in health and diseases. This is preceded by an outline of recent developments in the definition of DF, including the approval by authorities of health benefits of added fiber ingredients in foods, as well as criteria to be taken into account when evaluating the health effect of DF.

## 2. Background: the concept of dietary fiber

Over the years, the definition of DF, analytical methods and their effects on health and disease have been widely discussed. As indicated in the recent review by Stephen et al., a fair degree of uniformity currently exists in the definition of fiber, the method

\* Corresponding author. Metabolism and Nutrition Research Group, Louvain Drug Research Institute, Université catholique de Louvain, 73 av. E. Mounier box B1.73.11, B-1200, Brussels, Belgium.

E-mail address: [nathalie.delzenne@uclouvain.be](mailto:nathalie.delzenne@uclouvain.be) (N.M. Delzenne).

**List of abbreviations**

ANGPTL4	angiopoietin-related protein 4	IL	interleukin
AX	arabinoxylans	ITF	inulin-type fructans
AXOS	arabinoxyloligosaccharides	ISAPP	International Scientific Association for Probiotics and Prebiotics
BCFA	branched-chain fatty acids	LPL	lipoprotein lipase
DF	dietary fiber	LPS	lipopolysaccharide
EFSA	European Food Safety Authority	MU	monomeric units
EU	European Union	NSP	non-starch polysaccharides
FDA	United States Food & Drug Administration	PYY	peptide YY
FOS	fructo-oligosaccharides	RO	resistant oligosaccharides
GLP-1	glucagon-like peptide-1	RS	resistant starch
GOS	galacto-oligosaccharides	SCFA	short-chain fatty acids
HMOs	human milk oligosaccharides	WBE	wheat bran extract

used for analysis and the recommended amounts for consumption [4]. Gut microbiota related health benefits are not yet included in the current dietary and public health recommendations but, as indicated in this Opinion Paper, significant advances have been made to have clarifications about the physiological effects of DF to be taken into account for future recommendations [5,6].

The definition issued after the Codex Alimentarius in 2008 has a fair degree of uniformity [4,7]. DF is made up of carbohydrate polymers with three or more monomeric units (MU), which are neither digested nor absorbed in the human intestine and includes: (i) non-starch polysaccharides (NSP) from fruits, vegetables, cereals and tubers whether intrinsic or extracted, chemically, physically and/or enzymatically modified or synthetic ( $MU \geq 10$ ); (ii) resistant oligosaccharides (RO) ( $MU 3-9$ ); and (iii) resistant starch (RS) ( $MU \geq 10$ ). The Codex definition includes polymers with at least 10 monomeric units (MU) but leaves to national authorities the decision on whether or not to include carbohydrates with an MU number of 3–9. The European Union (EU) and other countries with an own fiber definition, e.g. the USA, Canada, China, Australia/New Zealand and, Japan include carbohydrates with  $MU \geq 3$  [4–6]. When extracted, chemically, physically and/or enzymatically modified or synthetic, generally accepted scientific evidence of benefits for health must be demonstrated to consider the polymer as DF. Most definitions also include ‘associated substances’, which are non-carbohydrate such as lignin and substances, which are present in cell walls linked to polysaccharides and quantified as DF by the accepted analytical methods.

These views are reflected in dietary recommendations worldwide, where only consumption of DF naturally present in food is emphasized, whereas there's still no reference to added, non-digested carbohydrate polymers, due to the limited body of evidence of benefits to health of these fibers. For instance, the European Food Safety Authority (EFSA), the United States Food & Drug Administration (FDA), and Health Canada approved health claims for a limited number of DF, including both some of the naturally present fibers and some added fibers, indicating that the criteria for approval of a health claim are considerably more strict than the criteria for getting approval as DF as was recently obtained in the USA and Canada for a wide range of added fibers.

Regarding the benefits for health, Codex states that DF generally present one or more of the following properties: (i) decrease intestinal transit time, increase stools bulk; (ii) fermentation by colonic microbiota; (iii) reduce blood total and/or LDL cholesterol levels; and (iv) reduce post-prandial blood glucose and/or insulin levels. These, or similar criteria, were included in the EU Directive 2008/100/EC and applied, in recent years, for evaluating the benefits to health of a wide range of fiber ingredients by Health

Canada's Food Directorate [6,8] and the FDA [5]. Both, Health Canada and the FDA concluded that, for most current commercially available DF, sufficient scientific evidence is available for including them in the list of compounds that can be officially considered as DF. The approved fibers include: (i) NSP including cellulose, hemicelluloses (i.e., arabinoxylans (AX)), mannans, pectins, and other hydrocolloids (i.e., gums, mucilages,  $\beta$ -glucans), inulin and fructans; (ii) RO including fructo-oligosaccharides (FOS), galacto-oligosaccharides (GOS); and (iii) RS [4]. Probably the list of approved fibers will grow further when studies provide evidence for new health benefits.

Regarding the role of colonic fermentation in attributing health benefits to fiber, there are some differences among countries. Health Canada requires “providing energy-yielding metabolites through colonic fermentation” emphasizing the production of short-chain fatty acids (SCFA). While colonic fermentation is not currently a physiological effect of fibers approved by FDA, fermentation-related criteria that apply are (i) “increasing mineral absorption” associated to the increased solubility and bioavailability through the production of SCFA, and (ii) “reducing energy intake” related to colonic fermentation of fibers. However, still, some discrepancies exist concerning the real contribution of SCFA as energy providers and/or as regulators of energy homeostasis. For each approved fiber, the primary benefit of health must be proven. In this sense, the fermentation-related criteria were chosen as primary end-points for a range of oligosaccharidic fibers, such as FOS (including inulins), GOS and other resistant oligosaccharides (i.e., isomalto-oligosaccharides, resistant maltodextrins, polydextrose). In EU, the evaluation is different, and the recognition of DF is case by case performed based on analytical criteria, through the widely accepted AOAC2009.01 standard method, or a similar approved method (taking into account the Codex definition and the EU definition with the  $MU \geq 3$ ). Nutrition facts information related to DF can then be put on product labels.

Contrary to the still widely accepted view that soluble fibers are fermentable and insoluble fibers are non-fermentable, almost all types of DF are fermentable, entirely or to some degree [4]. The difference is that some fibers are rapidly fermented by the colonic microbiota, whereas others are fermented more slowly, and in some instances to a limited extent. Although a classification according to the fermentability is difficult to establish since the evaluation has not been performed systematically for all DF, a few broad statements can be made. Soluble RO (but not viscous) are highly fermentable in the colon. Among insoluble NSP, the fermentability varies depending on the cereal and the tissue of the cell wall from which it is extracted. For instance, in maize, the bran is very poorly degraded compared to wheat bran [9]. At the same

time, within the wheat bran the fermentability is also different on the different tissues that constitute it and the milling settings [10]. In the aleurone layer, which represents approximately 40–50% of the wheat bran, there are AX and  $\beta$ -glucan [11]. These are well degraded when exposed to *in vitro* fermentation; however, other tissues also composing the wheat bran are not fermented although they contain a large amount of AX, cellulose, and lignins [12,13].

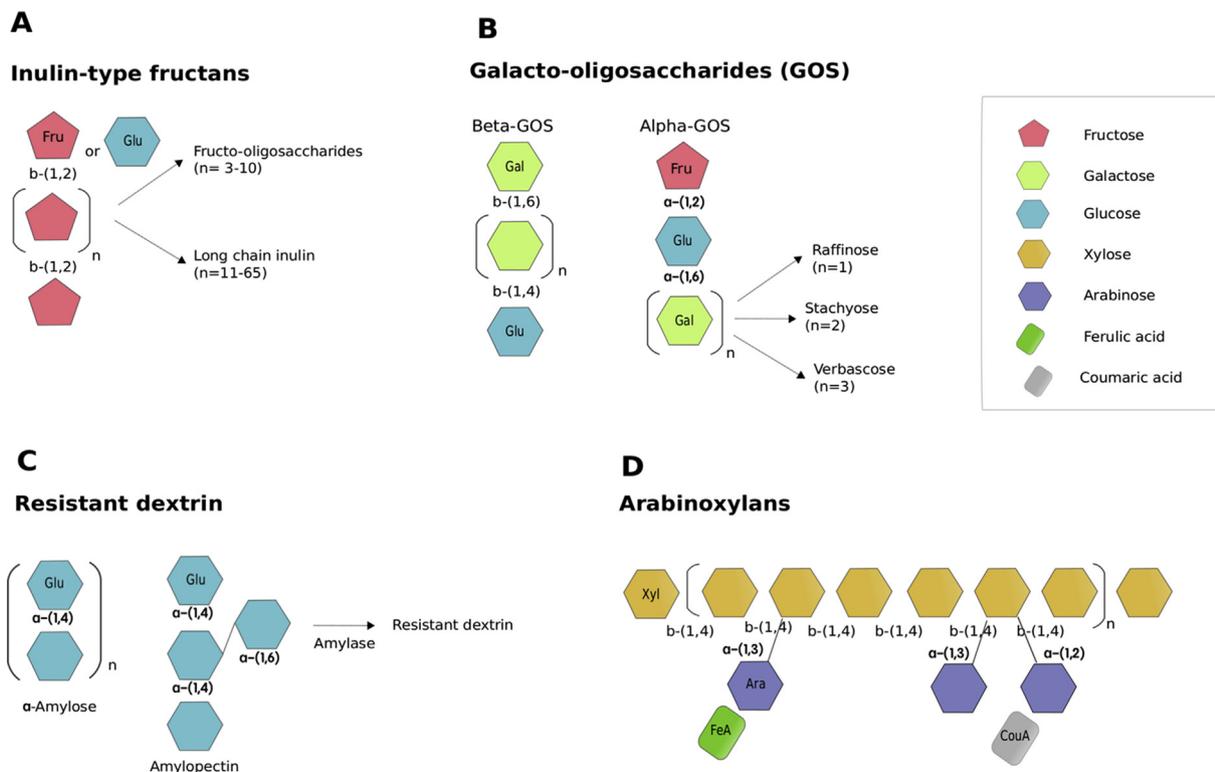
### 3. Dietary fibers with prebiotic properties

The term prebiotic, first introduced by Gibson & Roberfroid (1995) was initially defined as “a non-digestible food ingredient that beneficially affects the host by selectively stimulating the growth and/or activity of one or a limited number of bacteria in the colon, and thus improves host health” [14]. Tempting to classify microorganisms as beneficial or detrimental is complicated since the invasive or pathogenic properties of the bacteria depend on the whole microbial ecosystem and host gut homeostasis. In 2015, it was proposed an extension to the term prebiotic to “non-digestible compounds that, through their metabolism by microorganisms in the gut, modulate the composition and/or activity of the gut microbiota, thus, conferring a beneficial physiological effect on the host” [15]. In 2017, the International Scientific Association for Probiotics and Prebiotics (ISAPP) panel lastly updated the definition of a prebiotic as a “substrate that is selectively utilized by host microorganisms conferring a health benefit” [16]. This definition expands the concept of prebiotics to possibly include non-carbohydrate substances, applications to body sites other than the gastrointestinal tract, and diverse categories other than food. The requirement for selective microbiota-mediated mechanisms was retained and, beneficial health effects must be documented for a substance to be considered a prebiotic.

Next, we summarize the main reported effects of some prebiotics in intervention studies in humans. Note that currently and mostly for historical reasons, the majority of the scientific data related to prebiotic effects have been obtained using food ingredients/supplements belonging to the chemical groups known as inulin-type fructans (ITF) and GOS [14,17–20]. Besides, for the last 10 years, additional data have been obtained concerning the potential of other DF to modulate the gut microbiome. One example is the AX extracted from wheat bran and the hydrolysis product of AX so-called AXOS. The latter was the compound chosen by the MyNewGut consortium to explore its prebiotic properties as a potential intervention strategy to combat obesity. Consequently, the effects of AX and AXOS in the context of obesity are discussed in more detail throughout this Opinion Paper.

#### 3.1. Inulin-type fructans (ITF)

ITF are oligomers or polymers of fructose whose schematic representation appears in Fig. 1A. ITF are present in various vegetables, but can also be isolated from non-edible plant sources (like chicory roots) or synthesized from saccharose. Fructans have repeatedly demonstrated the capacity to selectively stimulate certain bacteria like *Bifidobacteria*, and besides, new analytical tools allow to demonstrate that additional changes in microbiota occur when feeding oligosaccharides. The ITF feeding provide changes in microbiota that can be related to changes in biomarkers related to health. For example, double-blind, randomized, crossover intervention showed that the treatment with ITF, but not the placebo, caused an increase in *Bifidobacterium* spp. and *Faecalibacterium prausnitzii*, and that both bacteria were negatively correlated with the seric levels of lipopolysaccharide (LPS) [21]. A more recent study assessed in healthy subjects the effect of ITF supplementation throughout a double-blind, randomized, cross-



**Fig. 1.** Schematic representation of the structure of A) inulin-type fructans, B) galacto-oligosaccharides (GOS), C) resistant dextrin, and D) arabinoxylans (Note that p-coumaric acid is present only in stems of grasses, not in grain).

over intervention combining ecosystem-wide microbiome and metabolome profiling techniques [22]. This study demonstrated that the effect of ITF supplementation on the fecal microbiota is mainly restricted to changes in *Anaerostipes*, *Bilophila* and, *Bifidobacterium* and concluding that ITF quite selectively influences the growth of a limited number of gut bacteria [22]. Furthermore, these authors found first indications that the observed reduction in *Bilophila*, a genus containing known pathobionts, is associated with enhanced host well-being assessed by physical discomfort and treatment satisfaction scores [22]. A second study, also published in 2017, described the beneficial effects of oligofructose-enriched inulin in children with overweight or obesity [23]. This study is relevant for public health since excess weight in childhood tends to persist into adulthood and is an early risk factor for obesity-associated morbidity and mortality [24]. Oligofructose-enriched inulin increased *Bifidobacterium* spp. numbers and significantly reduced body weight z-score, percent body fat, and serum level of interleukin (IL)-6 in children with overweight or obesity [23].

### 3.2. Galacto-oligosaccharides (GOS)

GOS are  $\beta$ -galactosides (terminal glucose and remaining galactose units linked together by  $\beta$ -glucosidic bonds) or  $\alpha$ -galactosides, such as raffinose (trisaccharide), stachyose (tetrasaccharide), and verbasose (pentasaccharide) (Fig. 1B). Even though there are many studies related to human milk oligosaccharides (HMOs) and their influence in the infant health [25], still is limited the number of studies reporting beneficial metabolic effects of GOS in the adult population. The available evidence shows, for example, that the supplementation with a GOS to healthy elderly volunteers decreased systemic and fecal pro-inflammatory markers associated with increases in *Bifidobacterium* spp., *Lactobacillus-Enterococcus* spp., and the *C. coccoides*–*E. rectale* group numbers, together with reductions in *Bacteroides* spp., *E. coli*, and *Desulfovibrio* spp. [26]. Another intervention study, but in this case enrolling overweight participants, showed that the supplementation with GOS improved insulin and lipid homeostasis and attenuated low-grade systemic inflammation [27]. In contrast, a more recent study in overweight or obese prediabetic subjects confirmed that the supplementation of GOS increased *Bifidobacterium* spp. abundance, as previously reported in healthy elderly volunteers, but was not associated with significant changes in insulin sensitivity or metabolic parameters [28].

### 3.3. Resistant dextrin

Wheat dextrin is a soluble fiber widely being used in the food industry because of its low viscosity and good consistency when added to water, beverages or soft food. Wheat dextrin is a glucose polymer derived from wheat or maize starch and formed by heating at high temperature followed by enzymatic (amylase) treatment to form a resistant starch (Fig. 1C). One study comparing the *in vitro* fermentability of wheat dextrin with that of inulin showed that wheat dextrin exhibited a unique fermentation pattern and produced total SCFA concentrations similar to inulin [29]. Several *in vitro* and *in vivo* studies (in rats and humans) have been undertaken to explore the potential prebiotic effects of wheat dextrin. Resistant dextrin has shown to increase lactobacilli and bifidobacteria, and reduce *Clostridium perfringens* when administered to healthy volunteers [30]. In another study with 40 female subjects, resistant dextrin supplementation not only increased Bacteroides, the predominant beneficial saccharolytic genus of a “normal” gut microbiota, but also decreased the numbers of pathogenic bacteria [31]. Interestingly, resistant dextrin supplementation can also

modulate inflammation and improve insulin resistance in women with type 2 diabetes [32]. However, additional studies are needed to determine whether the effect of resistant dextrin on the improvement in glucose homeostasis is linked to gut microbiota modulation.

### 3.4. Arabinoxylans (AX)

AX consists of a linear chain of residues of xylose to which units of arabinoses can be linked and whose degree of substitution is described as A/X ratio (Fig. 1D) [33]. Besides, in grain, ferulic acid can be attached to AX, whereas in stems of grasses, but not in grain, the bond of p-coumaric acid to AX has been also documented [34]. As explained above, aleurone is part of the bran. About 25% of AX are found in the starchy endosperm, 25% in aleurone and the remaining 50% are found in the other outer tissues of the grain [35]. Most AX in wheat bran are water-insoluble because of ferulic acid residues establishing crosslinks between AX and adjacent units of lignin [36]. AX are selectively degraded in the colon by intestinal bacteria expressing xylanases and arabinofuranosidases and represent a new class of prebiotics [37–39]. Until now, only a few studies investigated whether wheat-derived AX could have beneficial effects on host health by modulating the intestinal microbiota. Using two distinct *in vitro* models for the human gut, Van den Abbeele et al. have shown that a specific concentrate of water-extractable long chain AX and the well-established prebiotic inulin may be complementary as they both induced specific fermentation patterns within the intestinal microbiota with specific potential health benefits [40]. While AX specifically increased *Bifidobacterium longum* and propionate production, inulin increased *Bifidobacterium adolescentis* (among other bifidobacteria) and butyrate levels. Future research should establish how widespread these specific microbial responses to AX and ITF in human subjects. They suggest that AX seem to fulfill the requirements to be considered a promising prebiotic compound and that they might confer beneficial health effects through gut microbiota modulation, potentially in a more specific and potent manner as compared to inulin [40]. AXOS are hydrolysis products of AX and are characterized by their lower average degree of polymerization and their average degree of arabinose substitution [36,41]. Because of pre-hydrolysis, they are highly soluble and rapidly fermentable as shown *in vitro* experiments [42]. Many interventions studies with humans, enrolling healthy subjects or subjects with overweight or metabolic syndrome, have assessed the effects of wheat-derived AX or AXOS on metabolic parameters [43–56] (Table 1). The most consistent observation across studies is related to an improvement in the glucose homeostasis. For instance, one study in healthy young adults showed that white bread enriched with a high content of AXOS (18.4 g) has the potential to beneficially influence overnight glycemic regulation and gut fermentation (measured as the increase in breath H<sub>2</sub> and circulating SCFA) [55]. The latter observation was in agreement with another previous study that reported the same effect, but in which the prebiotic potential of AXOS was not linked to the host metabolism [57]. Additional studies are needed to determine whether the effect of wheat-derived AX or AXOS improvement in glucose homeostasis is linked to gut microbiota modulation. With this aim, the influence of AXOS-rich wheat bran extract (WBE) in overweight individuals on gut microbiota and metabolic risk markers has been studied by the MyNewGut consortium in a randomized cross-over trial (NCT02215343). This study is the first analyzing the effects of AXOS intake on gut microbiota composition by 16S rRNA sequencing in human. The main results demonstrated that AXOS exhibit the characteristic bifidogenic effect and promote the increase of a wide variety of butyrate producers [58].

**Table 1**  
Summary of the intervention studies performed in humans with arabinoxylans (AX) and arabinoxyloligosaccharides (AXOS) reporting effects on metabolic parameters.

Reference	Study design	Fiber treatment	Placebo treatment	Dose	Time	Study population	Size, n	Outcome
[43]	Single blind	Bread with low or high AX-rich fiber content	Control bread without AXs-rich fiber	0.6 or 12 g	3 d	Healthy individuals (5 men and 9 women) Aged 32.0 ± 6.6 BMI 22.7 ± 4.3	14	↓ postprandial glycaemia, improvement in the insulin response
[44]	Cross-over	AX-bread and muffins	Bread and muffins non supplemented	14–17 g	5 wk	Type 2 diabetes patients (6 male, 9 female) Aged 60 ± 2.0 BMI 28.1 ± 0.9	15	↓ fasting glycaemia, ↓ glycaemia and insulinaemia 2 h post OGTT
[45]	Cross-over	Bread rolls with AX	Bread rolls non supplemented	6 g	Acute	Healthy individuals (6 men and 9 women) Aged 26.4 ± 2.6 BMI 22.9 ± 2.7	15	=postprandial glycaemia, ↓ postprandial insulinaemia
[46,47]	Single blind, cross-over	Bread rolls with AX, and AX in powder	Isocaloric bread rolls and powder without AX	15 g	6 wk	Overweight individuals with insulin resistance (4 men and 7 women) Aged 55.5 ± 6.2 BMI 30.1 ± 5.7	11	↓ fasting glucose, ↓ TG ↓ apolipoprotein A-1 =insulin, adiponectin, leptin. After a liquid meal challenge test: ↓ postprandial glycaemia, ↓ insulin, ↓ TG, ↓ total plasma ghrelin ↑ Bifidobacteria ↓ urinary p-cresol excretion =total cholesterol, HDL, LDL, and TG
[48]	Cross-over	Crude AXOS	Maltodextrin	10 g <sup>a</sup>	3 wk	Healthy individuals (6 men and 14 women) Aged 24.0 ± 5.0 BMI 20.9 ± 2.3	20	↑ Bifidobacteria ↓ urinary p-cresol excretion =total cholesterol, HDL, LDL, and TG
[49]	Double blind, cross-over	RTEC with AXOS	Ready-to-eat cereal containing no AXOS	2.2 or 4.8 g	3 wk	Healthy individuals Men and women Aged not specified BMI not specified	55	=fasting glycaemia, ↓ fasting insulinaemia (2.2 g vs control), ↑ Bifidobacteria, ↓ butyric acid =total bacteria, Bacteroides, <i>Lactobacillus</i> spp., = <i>C. coccoides</i> , <i>Clostridium</i> clusters I and II, <i>F. prausnitzii</i> , ↑ Bifidobacteria, ↑ SCFA =total cholesterol, HDL, LDL, and TG ↓ p-cresol
[50]	Double blind, cross-over	Non-carbonated soft drinks with wheat bran extract rich in AXOS	Non-carbonated soft drinks non supplemented	2.4 or 8 g	3 wk	Healthy individuals (33 man and 30 women) Aged 42 ± 17 BMI 23.2 ± 3.2	63	↑ Bifidobacteria, ↑ SCFA =total cholesterol, HDL, LDL, and TG ↓ p-cresol
[51]	Cross-over	Semolina porridge with AX, RK, or AXRK	Semolina porridge non supplemented	3.5 g (AX) 4.7 g (RK) 4.4 g (AXRK)	Acute	Individuals with MeS (8 men and 7 women) Aged 63.5 ± 5.0 BMI 31.3 ± 2.7	15	AXRK: ↓ acute glucose, insulin, feeling of hunger AXRK and AX: ↑ plasma butyrate and acetate
[52]	Cross-over	Bread with AX, BG, or RK	Wheat bread non supplemented	7.1 g (AX) 2.6 g (BG) 6.1 g (RK)	Acute	Individuals with MeS (7 men and 8 women) Aged 62.8 ± 4.2 BMI 31.1 ± 3.2	15	BG and RK: ↓ postprandial glucose RK: ↓ insulin and GIP vs the other breads. BG: ↓ insulin more than AX AX, BG and RK: ↑ satiety feeling
[53]	Double blind, cross-over	Trial 1 and 2: RTEC with AXOS or RTEC with intact AXOS from flax	Trial 1 and 2: low-fiber RTEC (≠ E content) Trial 2: low-fiber RTEC (isocaloric)	15 g	Acute	Overweight women Trial 1: Aged 22.5 ± 0.6 BMI 27.0 ± 0.3, Trial 2: Aged 24.3 ± 0.5 BMI 27.4 ± 0.3	30 (trial 1) 36 (trial 2)	AXOS and flax: ↑ postprandial GLP-1 and PYY vs LF-iso =appetite response,
[54]	Double blind, cross-over	Bread with AX-enriched white flour	Bread with refined white flour	3.2 g	Acute	Healthy individuals (6 men and 18 women) Aged 34.5 ± 12.5 BMI 22.1 ± 2.5	24	↓ postprandial glucose

Table 1 (continued)

Reference	Study design	Fiber treatment	Placebo treatment	Dose	Time	Study population	Size, n	Outcome
[55]	Cross-over	White bread with AXOS + RS, high content of AXOS, or high content of RS	White bread non supplemented	8.9 (AXOS + RS) 18.4 (high AXOS)	Acute	Healthy individuals (9 men and 10 women) Aged 23.0 ± 0.4 BMI 22.2 ± 0.4	19	↓ glucose dose-dependently High AXOS improved insulin sensitivity ↑ Breath H <sub>2</sub> concentration and circulating SCFA in both breads with AXOS.
[56]	Double blind	AX in powder	Maltodextrin	7.5 or 15 g	6 w	Obese and overweight (25 men and 22 women) Aged 48.0 ± 1.6 BMI 31.0 ± 2.4	47	↑ Occludin expression in 7.5 AX group in colonic biopsies ↑ Claudin-3 and -4 in 15 AX group in colonic biopsies ↑ Microbiota diversity, ↑ SCFA, acetate, propionate, butyrate =intestinal permeability and tight function expression =no changes in metabolic markers

AX, arabinoxylans; AXOS, arabinosylo-oligosaccharides; AXRK, arabinoxylans + rye kernels; BMI, body mass index; d, days; GIP, glucose-dependent insulinotropic polypeptide; GLP-1, glucagon-like peptide-1; LF, low-fiber; OGTT, oral glucose tolerance test; PYY, peptide YY; RS, resistant starch; RTEC, ready-to-eat cereal; RK, rye kernels; SCFA, short-chain fatty acids; wk, weeks; BG, β-glucan; “=” means no significant changes versus control.

<sup>a</sup> The fiber treatment is named “crude AXOS” but the dose applies to the pure AXOS.

#### 4. Relevance of DF with prebiotic properties in the management of obesity and related metabolic diseases in human studies: focus on AX and AXOS

Obesity and related metabolic disorders is a context taken into account by EFSA when evaluating the interest of DF on weight maintenance, fiber intake and satiety [59]. The EFSA concluded that an increased intake of DF, both from naturally fiber-rich foods and added fiber or fiber supplements, has been shown to be related to improved weight maintenance in adults and sustained weight reduction in overweight subjects [59]. However, the effect of different sources or types of DF on body weight management in the context of obesity is poorly documented [60,61]. Increased satiety results from eating certain viscous types of DF, whereas the impact of such DF on energy intake or body weight, at least in the short term, can be inconsistent [62]. Among the factors associated with those effects, changes in lifestyle (i.e., higher levels of physical activity) can contribute. Some properties of high fiber diets, such as the replacement of high-energy foods, can also be involved in the improvement of glucose regulation and body weight [63].

Although there is strong epidemiologic evidence that DF intake is protective against overweight and obesity, a few studies demonstrate the fact that modulation of gut microbiota through DF consumption can manage metabolic diseases associated with obesity. Numerous studies have described the effect of prebiotics feeding (mostly 5–10% wt/wt food) on the evolution of body weight and fat mass in experimental animal models [20]. In studies of rodent models (lean, genetic or nutritional induced obese mice or rats), the decrease in fat mass following feeding with ingredients showing a prebiotic effect was associated with a reduction of food/energy intake [20,64]. The decrease in food/energy intake is not observed when ITF prebiotics are substituted by non-fermentable DF (microcrystalline cellulose), suggesting that at least the colonic fermentation plays a role in the modulation of food intake [65,66]. The decrease in food intake associated with prebiotics feeding in animals might be linked to the modulation of gastrointestinal peptides involved in the regulation of food intake. This particular finding, consisting in the promotion of glucagon-like peptide-1 (GLP-1) and peptide YY (PYY), has been confirmed in healthy human subjects resulting in changes in appetite sensations [67], even if the dose of prebiotics given to humans is far below the

one given to rodents (around 50 times higher in mice compared to humans).

Indeed, some studies suggest that DF with prebiotic potency improves anthropometric and metabolic outcomes in overweight and obese adults, thereby indicating that supplementation may improve health in these individuals [68]. However, the interpretation of these findings warrants caution because of the considerable between-study heterogeneity, for instance, the variability concerning the duration of the intervention. There is less report related to AX and wheat DF derivatives than reviews focusing on ITF, but the available epidemiological data describe that a high DF intake, mainly from whole-grain products, reduces the risk of obesity and type 2 diabetes mellitus [69]. All this lead us to select this type of DF and to unravel the potential mechanism linking the changes in microbiota and AX/wheat DF intake, with a focus on obesity and related metabolic disorders.

#### 5. Focus on mechanistic DF studies performed in the context of MyNewGut

##### 5.1. Mechanism of action of AXOS in preclinical animal models of obesity

The use of animal models is crucial to evaluate the mechanism by which the change in the gut microbiota driven by prebiotics may influence obesity-related diseases [70]. Throughout this section, we discuss the studies performed in animal models of diet-induced obesity supplemented either with AX, AXOS, and wheat bran as it constitutes the starting material. It is essential to keep in mind that as described above, AX represent the most abundant DF in wheat bran and that AX can then be hydrolyzed to produce AXOS [36,71]. The production of AXOS *in situ* from fiber-rich bread has been described when a mixture of xylanases comprising at least one thermophilic xylanase is added to the dough [72].

Regarding the potential effects of AX and AXOS, the first pieces of evidence were obtained using the raw materials used for the extraction, namely wheat bran crude fraction or the aleurone-enriched fraction [12,73]. The supplementation with one of these two wheat bran fractions in the high-fat diet (HFD)-fed mice showed, on one hand, that aleurone-enriched increased the numbers of *Bifidobacterium* spp. and *Lactobacillus* spp., and on the

other hand, that the crude fraction decreased IL-6 in the plasma [73]. Any of the two fractions affected the body weight, adiposity, glucose or lipid metabolism [73]. Later on, another study supplementing the HFD with AX showed that, whereas the HFD induced the expression of genes mediating fatty acid uptake, fatty acid oxidation and, inflammation, the supplementation with AX prevented the HFD-induced adiposity, body weight gain and insulin resistance [74]. These beneficial effects were accompanied by increases in *Bacteroides-Prevotella* spp., *Roseburia* spp., and *Bifidobacterium* spp. [74]. Next, the prebiotic potency of AXOS was tested in HFD-fed mice during eight weeks [75]. The authors observed an anti-obesogenic effect associated with a bloom in the genus *Bifidobacterium* spp.. Besides, novel insight tying the endocrine function and the gut barrier was proposed to explain the anti-obesogenic effects of AXOS [75]. The differential effect between the crude wheat bran and AXOS has been confirmed in one recent study [76]. AXOS was more efficient to reduce body weight gain, and adiposity than the two fractions of wheat bran with different particle size tested in parallel [76]. Besides and for the first time, the sequencing of the 16S rRNA gene showed that the microbial changes induced by AXOS in mice are profound and go beyond the bifidogenic effect and also confirmed in the mentioned one [76]. AXOS also increased in barrier-protecting bacteria like *Butyrivibrio* [76–78] and wholly blunted taxa related to bacteria associated with colitis and inflammatory disorders, such as *Turicibacter* and *Clostridium sensu stricto* [76]. The latter study represents an approach in which AXOS is administered together in an enriched-fat diet to test its preventive effects [76]. Besides, recently, AXOS has shown beneficial effects when administered after the pre-treatment of 4 weeks with an obesogenic diet [79]. In the MyNewGut project, we have explored the potential synergic or complementary effects of different DF utilized by indigenous intestinal human bacteria that can constitute the next generation of probiotics. In this context, AXOS was also proven to be the best fiber to stimulate the *in vitro* growth of the symbiont *Bacteroides uniformis* CECT 7771 along with up-regulation of the expression of genes involved in AXOS metabolism [80]. Ongoing animal trials also demonstrate that the combination of *B. uniformis* CECT 7771 and AXOS reduces body weight gain and fat mass to a greater extent than the bacterial strain or the fiber alone (unpublished data). All in all, AXOS could be a promising novel nutritional strategy to reduce the metabolic consequences of a regimen rich in fat. However, human intervention studies are warranted.

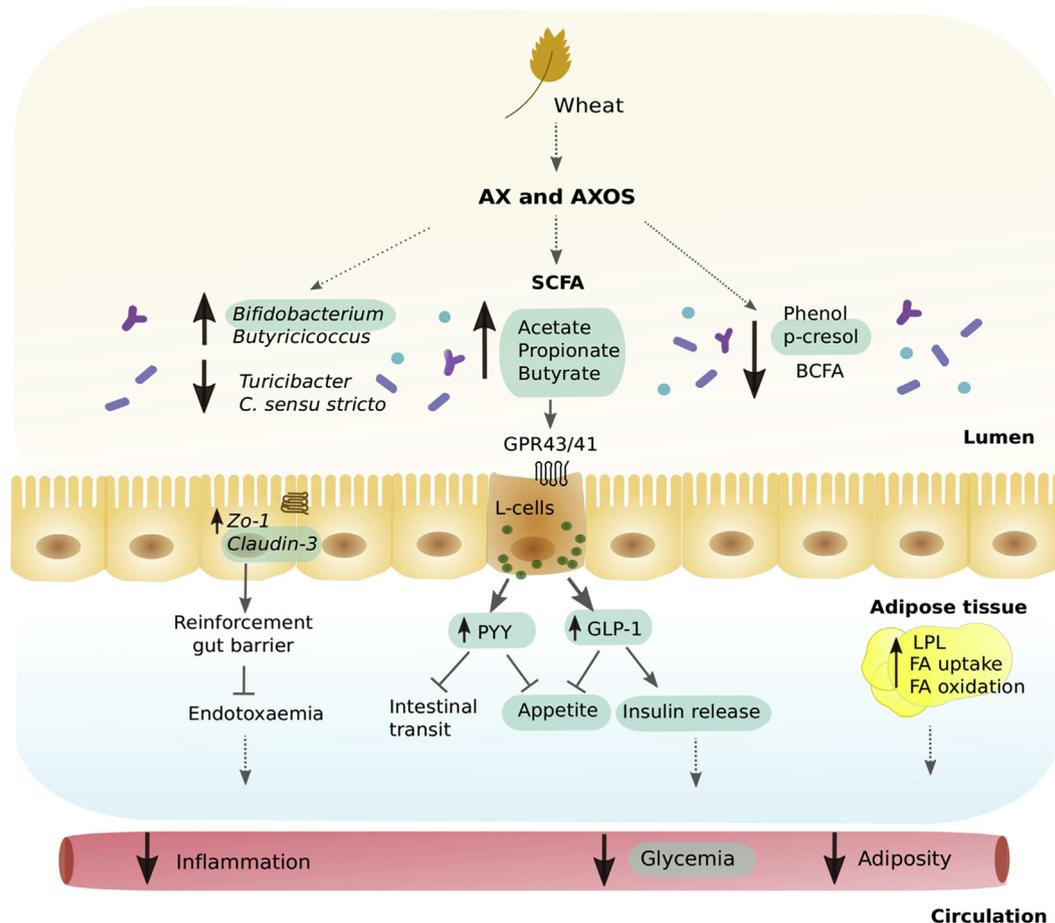
Preclinical models have pointed to several mechanisms to explain the link between the anti-obesity effect of AX and/or AXOS and the changes in the gut microbiota, and interestingly, some of these observations that have been confirmed in intervention studies with humans (Fig. 2). These include: (i) the modulation of entero-endocrine function; (ii) the regulation of the lipid metabolism; and (iii) the generation of SCFA. Initially, it was shown that ITF modulate the enteroendocrine function by increasing the number of L cells in the proximal colon of rats or mice. This increase was associated with the secretion of different peptides - GLP-1, GLP-2, and PYY - with critical roles in the control of gut barrier, appetite, and glucose homeostasis [52,65,81–84]. Similarly to what was shown for ITF, AXOS also can increase the level of circulating GLP-1 and PYY [75]. Moreover, AXOS supplementation upregulated the expression of the tight junction proteins *Zo-1* and *Claudin 3*, an effect that might explain the decrease in LPS concentration and the protection from metabolic related-metabolic alterations [75,85]. However, another study also evaluating AXOS reported no differences in markers of the gut barrier function despite AXOS promoted

barrier-protecting bacteria, such as *Butyrivibrio* [76]. Finally, the prebiotic-induced changes in the gut microbiota may also influence the expression of host genes involved in the control of fatty acid absorption, oxidation, and storage [86–88]. In the subcutaneous adipose tissue, the administration of AXOS caused a down-regulation of pathways involved in adipocyte differentiation, fatty acid uptake, fatty acid oxidation, that were up-regulated by the HFD [74]. Among the markers down-regulated by AXOS, it should be highlighted the expression of lipoprotein lipase (LPL) [74]. LPL is a specific enzyme which catalyzes the release of fatty acids from circulating triacylglycerol and lipoproteins in the muscle and the adipose tissue, and which activity is inhibited by the fasting-induced adipose factor (Fiaf, also known as angiopoietin-related protein 4 (ANGPTL4)) [89]. The suppression of Fiaf has been proposed as the critical piece for the microbiota-induced deposition of triglycerides in adipocytes [23]. However, to the best of our knowledge, to date, no mechanistic studies have been performed confirming this hypothesis.

### 5.2. Do bacterial metabolites mediate the beneficial effects of AXOS?

As described above, AXOS are metabolized by the gut microbiota resulting in the production of bacterial metabolites that are considered as crucial intermediates between the microbiota and the host. Therefore, it can be hypothesized that some of the effects of AXOS might be mediated by a modulation of the metabolic activity of the gut microbiota. AXOS are generally considered to promote saccharolytic fermentation, leading to increased production of SCFA. Indeed, consumption of bread containing AXOS increased fecal and plasmatic SCFA in healthy humans, notably with an increased acetate, propionate and butyrate in healthy adults [50], or only in butyrate [56,90]. SCFA are accepted to be crucial executors of diet-based microbial influence on the host health [91]. However, some studies did not observe an alteration of SCFA production after supplementation with AX-rich WBE [92,93], or even have reported reductions in butyrate [49]. These discrepancies could be related to different degrees of polymerization of AX that determines the gut segment where AXOS is fermented. Low degree of polymerization could induce a proximal AXOS fermentation and absorption of SCFA, resulting in a lack of apparently increased concentration in feces [92].

Besides SCFA, the gut microbiota can produce branched-chain fatty acids (BCFA) from the degradation of branched-chain amino acids, and *p*-cresol or indole from aromatic amino acids [94]. In healthy subjects, AXOS (or AX-rich WBE) reduced the fecal concentration of the gut microbiota-derived BCFA and the urinary excretion of *p*-cresol [72,92,93]. In obesity, there is also a decrease in BCFA content in the serum [95] and adipose tissue biopsies [96]. These changes might have physiological relevance since the *in vitro* exposure of adipocytes to two BCFA (isobutyric acid and isovaleric acid) influences adipocyte lipid and glucose metabolism [97]. Thus, the significance of the reduction of BCFA observed after the intake of AXOS or AX-rich WBE awaits to be investigated. Regarding the effects of derivatives from aromatic amino acids, it has been described that *p*-cresol has toxic effects for the intestinal epithelium [98], and consequently, low concentration of this metabolite is generally considered as beneficial for gut health. It can be hypothesized that AXOS-induced reduction of *p*-cresol production might have beneficial effects for gut barrier function in the context of obesity. One study in chronic kidney disease patients found that AXOS slightly decreased plasma trimethylamine-N-oxide [99], this bacterial



**Fig. 2.** Mechanisms evoked to understand the biological effect of arabinoxylans (AX) and arabinoxyloligosaccharides (AXOS) in the context of obesity. In animal models of diet induced-obesity, AX and/or AXOS produce changes in the taxonomy of the intestinal microbiota and its activity (production of bacterial metabolites). At the intestinal level, these changes are associated with a reinforcement of the intestinal barrier and with stimulation of the enteroendocrine system to produce hormones that regulate appetite and homeostasis of glucose. In the adipose tissue, AX and/or AXOS influence the regulation of lipid metabolism which ultimately reduces the development of adiposity. The observations that have been confirmed in intervention studies with humans appears labeled in blue. FA, fatty acid; GLP-1, glucagon-like peptide-1; LPL, lipoprotein lipase; PYY, peptide YY; Zo-1, Zonula occludens.

metabolite being implicated in cardiovascular disease progression [100]. Although this finding should be confirmed in obese subjects, the AX-induced reduction of trimethylamine-N-oxide could contribute to the beneficial metabolic effects of AXOS.

Interestingly, some inter-individual differences have been observed regarding the AX-induced modulation of the metabolic activity of the gut microbiota [92]. However, the features of the gut microbiota of AXOS responders remain to be determined. Importantly, metabolization by the gut microbiota of ferulic acid associated with AXOS might also result in the production of bacterial bioactive metabolites that could underlie AXOS metabolic effects [101]. In conclusion, there is strong evidence that AX modulates the metabolic activity of the gut microbiota. However, these data should be confirmed in obese subjects, and the relative contribution of the bacterial metabolites to the beneficial effects of AXOS should be further investigated. The full integration of metagenomic, metabolomics and lipidomic data derived from subjects enrolled into the MyNewGut 4-week AXOS intervention also proves that the consumption of this DF changed the gut microbiome gene functions and host-microbe related metabolites with potential impact on glucose homeostasis. Moreover, the activation of specific microbial metabolic circuits in particular gut microbes strongly indicates that sustained consumption of AXOS in time would be central for maintenance of metabolic health in humans [102].

## 6. DF with prebiotic properties: outcomes and needs to progress with dietary guidelines and innovation in human nutrition

In this last section, we aim to address the following question: can we elaborate dietary recommendations of DF taking into account their interaction with the gut microbiota? The current dietary recommendations refer to a certain amount of total DF to be eaten in g per day or per 1000 kcal intake. The discrepancy between fiber solubility and fermentability, the proportion of soluble versus insoluble DF does not appear as essential to take into account when establishing dietary recommendations by the corresponding authorities (Table 2).

The concept of “modulation of gut microbiota activity and/or composition by prebiotic DF” is interesting, but it is rather difficult to establish at which doses a prebiotic DF must be ingested to change the gut microbiota significantly, and how it is related to health effect. For some prebiotic DF, some bacteria (i.e., *Bifidobacteria* for inulin-type fructans) appear as “biomarkers” of the microbial response rather than as a key player in the health effects, that are merely not attributable to single species. Most intervention studies with prebiotic DF have been conducted with “purified” or isolated DF, at relatively high doses (around 20 g for most studies) and we do not know if those prebiotic DF present in a natural food matrix will modulate the gut microbiota. How health outcomes

**Table 2**  
Recommendation for daily dietary (DF) intake adapted from Lockyer et al. [103].

Reference	Region	Recommendation	Issuing body
[104]	EU	25 g/day for adults 2 g/MJ for children from the age of one year	EFSA
[105]	UK	30 g/day for adults 15 g/day (age 2–5) 20 g/day (age 5–11) 25 g/day (age 11–16) 30 g/day (age 16–18)	UK's SACN
[106]	Nordic countries	25–35 g for adults	The Nordic Council of Ministers
[107]	US	33.6 g for men 28 g for women (14 g/1000 kcal)	USDA
[108]	Australia and New Zealand	30 g for men 25 g for women	NHMRC

EFSA: European Food Safety Authority; EU, European Union; FSAI, Food Safety Authority of Ireland; NHMRC, National Health and Medical Research Council; SACN, Scientific Advisory Committee on Nutrition; UK, United Kingdom; USDA, United States Department of Agriculture.

(positive or negative) relate to specific metabolites or microbial components in humans has to be established in the future. The task is not easy, in particular, because appropriate (and consensual) quantitative and qualitative analysis of DF are missing in most food composition tables, but also because dealing with microbiota complexity, requires that the scientists involved in this domain agree on the adequate methodology to assess human gut microbiota fermentation and microbiome assessment. Besides, the setting of dietary recommendation should take into account the problems of discomfort linked to the consumption of DF. For instance, a mild increase in flatulence has been reported in studies testing a dose of 10 g per day of AXOS [48], but in lower doses (2.2 or 4.8) no effect was noticed [49]. Consequently, the balance between tolerance and the positive impact on the microbiota is an issue that the future dietary recommendation should also tackle.

In conclusion, upon the data obtained in the MyNewGut project and recent publications in the field, we could progress in the evaluation of the fiber sources that beneficially impact specific components of the gut microbiota and metabolism and contribute to discovering new players and mechanisms of action that could support specific health-outcomes.

### Duality of interest

CSIC has received research funding from LNC and Vision Global.

### Conflicts of interest

None declared.

### Contribution statement

NMD, MO, AMN, MB, and JWvdK wrote the manuscript. NMD coordinated the work. MO prepared the tables and figures. All authors (NMD, MO, AMN, MB, LK, TML, AB-P, MR-P, VG-C, DB, YS, JWvdK) contributed to discussion, editing and approval of the final manuscript.

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### References

- [1] Sanz Y, Romani-Perez M, Benitez-Paez A, Portune KJ, Brigidi P, Rampelli S, et al. Towards microbiome-informed dietary recommendations for promoting metabolic and mental health: Opinion papers of the MyNewGut project. *Clin Nutr* 2018;37(6):2191–7. Part A.
- [2] Sonnenburg JL, Backhed F. Diet-microbiota interactions as moderators of human metabolism. *Nature* 2016;535(7610):56–64.
- [3] O'Keefe SJ, Li JV, Lahti L, Ou J, Carbonero F, Mohammed K, et al. Fat, fibre and cancer risk in African Americans and rural Africans. *Nat Commun* 2015;6:6342.
- [4] Stephen AM, Champ MM, Cloran SJ, Fleith M, van Lieshout L, Mejbom H, et al. Dietary fibre in Europe: current state of knowledge on definitions, sources, recommendations, intakes and relationships to health. *Nutr Res Rev* 2017;30(2):149–90.
- [5] FDA. Review of the scientific evidence on the physiological effects of certain non-digestible carbohydrates. 2018.
- [6] Directorate HCSF. List of dietary fibres reviewed and accepted by health Canada's food directorate. 2017.
- [7] Verspreet J, Damen B, Broekaert WF, Verbeke K, Delcour JA, Courtin CM. A critical look at prebiotics within the dietary fiber concept. *Annu Rev Food Sci Technol* 2016;7:167–90.
- [8] Directorate HCSF. Policy for labelling and advertising of dietary fibre-containing food products. 2012.
- [9] Rose DJ, Patterson JA, Hamaker BR. Structural differences among alkali-soluble arabinoxylans from Maize (*Zea mays*), Rice (*Oryza sativa*), and Wheat (*Triticum aestivum*) brans influence human fecal fermentation profiles. *J Agric Food Chem* 2010;58(1):493–9.
- [10] Hemery Y, Lullien-Pellerin V, Rouau X, Abecassis J, Samson MF, Aman P, et al. Biochemical markers: efficient tools for the assessment of wheat grain tissue proportions in milling fractions. *J Cereal Sci* 2009;49(1):55–64.
- [11] Saulnier L, Guillon F, Chateigner-Boutin AL. Cell wall deposition and metabolism in wheat grain. *J Cereal Sci* 2012;56(1):91–108.
- [12] Amrein TM, Gränicher P, Arrigoni E, Amadó R. In vitro digestibility and colonic fermentability of aleurone isolated from wheat bran. *LWT - Food Sci Technol* 2003;36(4):451–60.
- [13] Brouns F, Hemery Y, Price R, Anson NM. Wheat aleurone: separation, composition, health aspects, and potential food use. *Crit Rev Food Sci Nutr* 2012;52(6):553–68.
- [14] Gibson GR, Roberfroid MB. Dietary modulation of the human colonic microbiota: introducing the concept of prebiotics. *J Nutr* 1995;125(6):1401–12.
- [15] Bindels LB, Delzenne NM, Cani PD, Walter J. Towards a more comprehensive concept for prebiotics. *Nat Rev Gastroenterol Hepatol* 2015;12(5):303–10.
- [16] Gibson GR, Hutkins R, Sanders ME, Prescott SL, Reimer RA, Salminen SJ, et al. Expert consensus document: the International Scientific Association for Probiotics and Prebiotics (ISAPP) consensus statement on the definition and scope of prebiotics. *Nat Rev Gastroenterol Hepatol* 2017;14(8):491–502.
- [17] Reid G, Sanders ME, Gaskins HR, Gibson GR, Mercenier A, Rastall R, et al. New scientific paradigms for probiotics and prebiotics. *J Clin Gastroenterol* 2003;37(2):105–18.
- [18] Gibson GR, Probert HM, Loo JV, Rastall RA, Roberfroid MB. Dietary modulation of the human colonic microbiota: updating the concept of prebiotics. *Nutr Res Rev* 2004;17(2):259–75.
- [19] Roberfroid M. Prebiotics: the concept revisited. *J Nutr* 2007;137(3 Suppl 2):830S–75S.
- [20] Roberfroid M, Gibson GR, Hoyle L, McCartney AL, Rastall R, Rowland I, et al. Prebiotic effects: metabolic and health benefits. *Br J Nutr* 2010;104(Suppl 2):S1–63.
- [21] Dewulf EM, Cani PD, Claus SP, Fuentes S, Puylaert PG, Neyrinck AM, et al. Insight into the prebiotic concept: lessons from an exploratory, double blind intervention study with inulin-type fructans in obese women. *Gut* 2013;62(8):1112–21.
- [22] Vandeputte D, Falony G, Vieira-Silva S, Wang J, Sailer M, Theis S, et al. Prebiotic inulin-type fructans induce specific changes in the human gut microbiota. *Gut* 2017;66(11):1968–74.
- [23] Nicolucci AC, Hume MP, Martinez I, Mayengbam S, Walter J, Reimer RA. Prebiotics reduce body fat and alter intestinal microbiota in children who are overweight or with obesity. *Gastroenterology* 2017;153(3):711–22.
- [24] Weiss R, Caprio S. The metabolic consequences of childhood obesity. *Best Pract Res Clin Endocrinol Metabol* 2005;19(3):405–19.
- [25] Triantis V, Bode L, van Neerven RJJ. Immunological effects of human milk oligosaccharides. *Front Pediatr* 2018;6:190.
- [26] Vulevic J, Drakoularakou A, Yaqoob P, Tzortzis G, Gibson GR. Modulation of the fecal microflora profile and immune function by a novel trans-galactooligosaccharide mixture (B-GOS) in healthy elderly volunteers. *Am J Clin Nutr* 2008;88(5):1438–46.

- [27] Vulevic J, Juric A, Tzortzis G, Gibson GR. A mixture of transgalactooligosaccharides reduces markers of metabolic syndrome and modulates the fecal microbiota and immune function of overweight adults. *J Nutr* 2013;143(3):324–31.
- [28] Canfora EE, van der Beek CM, Hermes GDA, Goossens GH, Jocken JWE, Holst JJ, et al. Supplementation of diet with galacto-oligosaccharides increases bifidobacteria, but not insulin sensitivity, in obese prediabetic individuals. *Gastroenterology* 2017;153(1):87–97 e3.
- [29] Stewart ML, Savarino V, Slavin JL. Assessment of dietary fiber fermentation: effect of *Lactobacillus reuteri* and reproducibility of short-chain fatty acid concentrations. *Mol Nutr Food Res* 2009;53(Suppl 1):S114–20.
- [30] Lefranc-Millot C, Guerin-Deremaux L, Wils D, Neut C, Miller LE, Saniez-Degrave MH. Impact of a resistant dextrin on intestinal ecology: how altering the digestive ecosystem with NUTRIOSE(R), a soluble fibre with prebiotic properties, may be beneficial for health. *J Int Med Res* 2012;40(1):211–24.
- [31] Elli M, Cattivelli D, Soldi S, Bonatti M, Morelli L. Evaluation of prebiotic potential of refined psyllium (*Plantago ovata*) fiber in healthy women. *J Clin Gastroenterol* 2008;42(Suppl 3 Pt 2):S174–6.
- [32] Aliasgharzadeh A, Dehghan P, Gargari BP, Asghari-Jafarabadi M. Resistant dextrin, as a prebiotic, improves insulin resistance and inflammation in women with type 2 diabetes: a randomised controlled clinical trial. *Br J Nutr* 2015;113(2):321–30.
- [33] Izydorczyk B. Cereal Arabinoxylans: advances in structure and physicochemical properties. *Carbohydr Polym* 1995;28:33–48.
- [34] Chateigner-Boutin AL, Ordaz-Ortiz JJ, Alvarado C, Bouchet B, Durand S, Verherbruggen Y, et al. Developing pericarp of maize: a model to study arabinoxylan synthesis and feruloylation. *Front Plant Sci* 2016;7:1476.
- [35] Marcotuli I, Hsieh YS, Lahnstein J, Yap K, Burton RA, Blanco A, et al. Structural variation and content of arabinoxylans in endosperm and bran of durum wheat (*Triticum turgidum* L.). *J Agric Food Chem* 2016;64(14):2883–92.
- [36] Iiyama K, Lam T, Stone BA. Covalent cross-links in the cell wall. *Plant Physiol* 1994;104(2):315–320.
- [37] Grootaert C, Van den Abbeele P, Marzorati M, Broekaert WF, Courtin CM, Delcour JA, et al. Comparison of prebiotic effects of arabinoxylan oligosaccharides and inulin in a simulator of the human intestinal microbial ecosystem. *FEMS Microbiol Ecol* 2009;69(2):231–42.
- [38] Vardakou M, Palop CN, Christakopoulos P, Faulds CB, Gasson MA, Narbad A. Evaluation of the prebiotic properties of wheat arabinoxylan fractions and induction of hydrolase activity in gut microflora. *Int J Food Microbiol* 2008;123(1–2):166–70.
- [39] Hughes SA, Shewry PR, Li L, Gibson GR, Sanz ML, Rastall RA. In vitro fermentation by human fecal microflora of wheat arabinoxylans. *J Agric Food Chem* 2007;55(11):4589–95.
- [40] Van den Abbeele P, Venema K, Van de Wiele T, Verstraete W, Possemiers S. Different human gut models reveal the distinct fermentation patterns of Arabinoxylan versus inulin. *J Agric Food Chem* 2013;61(41):9819–27.
- [41] Van Craeyveld V, Swennen K, Dornez E, Van de Wiele T, Marzorati M, Verstraete W, et al. Structurally different wheat-derived arabinoxylan oligosaccharides have different prebiotic and fermentation properties in rats. *J Nutr* 2008;138(12):2348–55.
- [42] Sanchez JI, Marzorati M, Grootaert C, Baran M, Van Craeyveld V, Courtin CM, et al. Arabinoxylan-oligosaccharides (AXOS) affect the protein/carbohydrate fermentation balance and microbial population dynamics of the Simulator of Human Intestinal Microbial Ecosystem. *Microb Biotechnol* 2009;2(1):101–13.
- [43] Lu ZX, Walker KZ, Muir JG, Mascara T, O'Dea K. Arabinoxylan fiber, a byproduct of wheat flour processing, reduces the postprandial glucose response in normoglycemic subjects. *Am J Clin Nutr* 2000;71(5):1123–8.
- [44] Lu ZX, Walker KZ, Muir JG, O'Dea K. Arabinoxylan fibre improves metabolic control in people with Type II diabetes. *Eur J Clin Nutr* 2004;58(4):621–8.
- [45] Mohlig M, Koebnick C, Weickert MO, Lueder W, Otto B, Steiniger J, et al. Arabinoxylan-enriched meal increases serum ghrelin levels in healthy humans. *Horm Metab Res* 2005;37(5):303–8.
- [46] Garcia AL, Steiniger J, Reich SC, Weickert MO, Harsch I, Machowetz A, et al. Arabinoxylan fibre consumption improved glucose metabolism, but did not affect serum adipokines in subjects with impaired glucose tolerance. *Horm Metab Res* 2006;38(11):761–6.
- [47] Garcia AL, Otto B, Reich SC, Weickert MO, Steiniger J, Machowetz A, et al. Arabinoxylan consumption decreases postprandial serum glucose, serum insulin and plasma total ghrelin response in subjects with impaired glucose tolerance. *Eur J Clin Nutr* 2007;61(3):334–41.
- [48] Cloetens L, Broekaert WF, Delaet Y, Ollievier F, Courtin CM, Delcour JA, et al. Tolerance of arabinoxylan-oligosaccharides and their prebiotic activity in healthy subjects: a randomised, placebo-controlled cross-over study. *Br J Nutr* 2010;103(5):703–13.
- [49] Maki KC, Gibson GR, Dickmann RS, Kendall CW, Chen CY, Costabile A, et al. Digestive and physiologic effects of a wheat bran extract, arabinoxylan-oligosaccharide, in breakfast cereal. *Nutrition* 2012;28(11–12):1115–21.
- [50] Francois IE, Lescroart O, Veraverbeke WS, Marzorati M, Possemiers S, Evenepoel P, et al. Effects of a wheat bran extract containing arabinoxylan oligosaccharides on gastrointestinal health parameters in healthy adult human volunteers: a double-blind, randomised, placebo-controlled, cross-over trial. *Br J Nutr* 2012;108(12):2229–42.
- [51] Hartvigsen ML, Laerke HN, Overgaard A, Holst JJ, Bach Knudsen KE, Hermansen K. Postprandial effects of test meals including concentrated arabinoxylan and whole grain rye in subjects with the metabolic syndrome: a randomised study. *Eur J Clin Nutr* 2014;68(5):567–74.
- [52] Hartvigsen ML, Gregersen S, Laerke HN, Holst JJ, Bach Knudsen KE, Hermansen K. Effects of concentrated arabinoxylan and beta-glucan compared with refined wheat and whole grain rye on glucose and appetite in subjects with the metabolic syndrome: a randomized study. *Eur J Clin Nutr* 2014;68(1):84–90.
- [53] Lafond DW, Greaves KA, Maki KC, Leidy HJ, Romsos DR. Effects of two dietary fibers as part of ready-to-eat cereal (RTEC) breakfasts on perceived appetite and gut hormones in overweight women. *Nutrients* 2015;7(2):1245–66.
- [54] Giulia Falchi A, Grecchi I, Muggia C, Palladini G, Perlini S. Effects of a bioavailable arabinoxylan-enriched white bread flour on postprandial glucose response in normoglycemic subjects. *J Diet Suppl* 2016;13(6):626–33.
- [55] Boll EV, Ekstrom LM, Courtin CM, Delcour JA, Nilsson AC, Bjorck IM, et al. Effects of wheat bran extract rich in arabinoxylan oligosaccharides and resistant starch on overnight glucose tolerance and markers of gut fermentation in healthy young adults. *Eur J Nutr* 2016;55(4):1661–70.
- [56] Salden BN, Troost FJ, Wilms E, Truchado P, Vilchez-Vargas R, Pieper DH, et al. Reinforcement of intestinal epithelial barrier by arabinoxylans in overweight and obese subjects: a randomized controlled trial: arabinoxylans in gut barrier. *Clin Nutr* 2018;37(2):471–80.
- [57] Cloetens L, De Preter V, Swennen K, Broekaert WF, Courtin CM, Delcour JA, et al. Dose-response effect of arabinoxylan oligosaccharides on gastrointestinal motility and on colonic bacterial metabolism in healthy volunteers. *J Am Coll Nutr* 2008;27(4):512–8.
- [58] Kjølbæk L, Benítez-Páez A, Gómez del Pulgar EM, Brahe LK, Liebisch G, Matysik S, et al. Arabinoxylan oligosaccharides and polyunsaturated fatty acid effects on gut microbiota and metabolic markers in overweight individuals with signs of metabolic syndrome: a randomized cross-over trial. *Clin Nutr* 2020;39(1):67–79. <https://doi.org/10.1016/j.clnu.2019.01.012>.
- [59] EFSA Panel on Dietetic Products NaA. Scientific Opinion on the substantiation of health claims related to konjac mannan (glucomannan) and reduction of body weight (ID 854, 1556, 3725), reduction of post-prandial glycaemic responses (ID 1559), maintenance of normal blood glucose concentrations (ID 835, 3724), maintenance of normal (fasting) blood concentrations of triglycerides (ID 3217), maintenance of normal blood cholesterol concentrations (ID 3100, 3217), maintenance of normal bowel function (ID 834, 1557, 3901) and decreasing potentially pathogenic gastro-intestinal microorganisms (ID 1558) pursuant to Article 13(1) of Regulation (EC) No 1924/2006. *EFSA J* 2010;8:1798–825.
- [60] Davis HC. Can the gastrointestinal microbiota be modulated by dietary fibre to treat obesity? *Ir J Med Sci* 2018;187(2):393–402.
- [61] Wanders AJ, van den Borne JJ, de Graaf C, Hulshof T, Jonathan MC, Kristensen M, et al. Effects of dietary fibre on subjective appetite, energy intake and body weight: a systematic review of randomized controlled trials. *Obes Rev* 2011;12(9):724–39.
- [62] Thompson SV, Hannon BA, An R, Holscher HD. Effects of isolated soluble fiber supplementation on body weight, glycemia, and insulinemia in adults with overweight and obesity: a systematic review and meta-analysis of randomized controlled trials. *Am J Clin Nutr* 2017;106(6):1514–28.
- [63] Kellow NJ, Coughlan MT, Reid CM. Metabolic benefits of dietary prebiotics in human subjects: a systematic review of randomised controlled trials. *Br J Nutr* 2014;111(7):1147–61.
- [64] Delzenne NM, Neyrinck AM, Cani PD. Modulation of the gut microbiota by nutrients with prebiotic properties: consequences for host health in the context of obesity and metabolic syndrome. *Microb Cell Factories* 2011;10(1):S10.
- [65] Cani PD, Possemiers S, Van de Wiele T, Guiot Y, Everard A, Rottier O, et al. Changes in gut microbiota control inflammation in obese mice through a mechanism involving GLP-2-driven improvement of gut permeability. *Gut* 2009;58(8):1091–103.
- [66] Daubioul C, Rousseau N, Demeure R, Gallez B, Taper H, Declercq B, et al. Dietary fructans, but not cellulose, decrease triglyceride accumulation in the liver of obese Zucker fa/fa rats. *J Nutr* 2002;132(5):967–73.
- [67] Cani PD, Lecourt E, Dewulf EM, Sohet FM, Pachikian BD, Naslain D, et al. Gut microbiota fermentation of prebiotics increases satiety and incretin gut peptide production with consequences for appetite sensation and glucose response after a meal. *Am J Clin Nutr* 2009;90(5):1236–43.
- [68] Barczynska R, Bandurska K, Slizewska K, Litwin M, Szalecki M, Libudzisz Z, et al. Intestinal microbiota, obesity and prebiotics. *Pol J Microbiol* 2015;64(2):93–100.
- [69] Hauner H, Bechthold A, Boeing H, Bronstrup A, Buyken A, Leschik-Bonnet E, et al. Evidence-based guideline of the German Nutrition Society: carbohydrate intake and prevention of nutrition-related diseases. *Ann Nutr Metab* 2012;60(1):1–58.
- [70] Neyrinck AMSV, Lockett T, Haller D, Delzenne NM. Microbiome and metabolic disorders related to obesity: which lessons to learn from experimental models? *Trends Food Sci Technol* 2016;57:256–64.
- [71] Swennen KCC, Lindemans GCJE, Delcour JA. Large-scale production and characterisation of wheat bran arabinoxylan oligosaccharides. *J Sci Food Agric* 2006;86:1722–31.
- [72] Damen B, Cloetens L, Broekaert WF, Francois I, Lescroart O, Trogh I, et al. Consumption of breads containing in situ-produced arabinoxylan

- oligosaccharides alters gastrointestinal effects in healthy volunteers. *J Nutr* 2012;142(3):470–7.
- [73] Neyrinck AM, De Backer F, Cani PD, Bindels LB, Stroobants A, Portetelle D, et al. Immunomodulatory properties of two wheat bran fractions - aleurone-enriched and crude fractions - in obese mice fed a high fat diet. *Int Immunopharmacol* 2008;8(10):1423–32.
- [74] Neyrinck AM, Possemiers S, Druart C, Van de Wiele T, De Backer F, Cani PD, et al. Prebiotic effects of wheat arabinoxylan related to the increase in bifidobacteria, Roseburia and Bacteroides/Prevotella in diet-induced obese mice. *PLoS One* 2011;6(6):e20944.
- [75] Neyrinck AM, Van Hee VF, Piront N, De Backer F, Toussaint O, Cani PD, et al. Wheat-derived arabinoxylan oligosaccharides with prebiotic effect increase satiety and modulation of the gut microbiota both determine the effect of wheat bran fractions on adiposity. *Sci Rep* 2017;7(1):5621.
- [76] Suriano F, Bindels LB, Verspreet J, Courtin CM, Verbeke K, Cani PD, et al. Fat binding capacity and modulation of the gut microbiota both determine the effect of wheat bran fractions on adiposity. *Sci Rep* 2017;7(1):5621.
- [77] Xiao S, Fei N, Pang X, Shen J, Wang L, Zhang B, et al. A gut microbiota-targeted dietary intervention for amelioration of chronic inflammation underlying metabolic syndrome. *FEMS Microbiol Ecol* 2014;87(2):357–67.
- [78] Devriese S, Eeckhaut V, Geirnaert A, Van den Bossche L, Hindryckx P, Van de Wiele T, et al. Reduced mucosa-associated *Butyrivibrio* activity in patients with ulcerative colitis correlates with aberrant claudin-1 expression. *J Crohns Colitis* 2017;11(2):229–36.
- [79] Neyrinck AM, Hiel S, Bouzin C, Campayo VG, Cani PD, Bindels LB, et al. Wheat-derived arabinoxylan oligosaccharides with bifidogenic properties abolishes metabolic disorders induced by western diet in mice. *Nutr Diabetes* 2018;8(1):15.
- [80] Benítez-Páez A, Gomez Del Pulgar EM, Sanz Y. The glycolytic versatility of *Bacteroides uniformis* CECT 7771 and its genome response to oligo and polysaccharides. *Front Cell Infect Microbiol* 2017;7:383.
- [81] Cani PD, Knauf C, Iglesias MA, Drucker DJ, Delzenne NM, Burcelin R. Improvement of glucose tolerance and hepatic insulin sensitivity by oligofructose requires a functional glucagon-like peptide 1 receptor. *Diabetes* 2006;55(5):1484–90.
- [82] Cani PD, Dewever C, Delzenne NM. Inulin-type fructans modulate gastrointestinal peptides involved in appetite regulation (glucagon-like peptide-1 and ghrelin) in rats. *Br J Nutr* 2004;92(3):521–6.
- [83] Cani PD, Neyrinck AM, Maton N, Delzenne NM. Oligofructose promotes satiety in rats fed a high-fat diet: involvement of glucagon-like Peptide-1. *Obes Res* 2005;13(6):1000–7.
- [84] Chambers ES, Viardot A, Psichas A, Morrison DJ, Murphy KG, Zaccarelli SE, et al. Effects of targeted delivery of propionate to the human colon on appetite regulation, body weight maintenance and adiposity in overweight adults. *Gut* 2015;64(11):1744–54.
- [85] Cani PD, Amar J, Iglesias MA, Poggi M, Knauf C, Bastelica D, et al. Metabolic endotoxemia initiates obesity and insulin resistance. *Diabetes* 2007;56(7):1761–72.
- [86] Bindels LB, Beck R, Schakman O, Martin JC, De Backer F, Sohet FM, et al. Restoring specific lactobacilli levels decreases inflammation and muscle atrophy markers in an acute leukemia mouse model. *PLoS One* 2012;7(6):e37971.
- [87] Backhed F, Ding H, Wang T, Hooper LV, Koh GY, Nagy A, et al. The gut microbiota as an environmental factor that regulates fat storage. *Proc Natl Acad Sci U S A* 2004;101(44):15718–23.
- [88] Aronsson L, Huang Y, Parini P, Korach-Andre M, Hakansson J, Gustafsson JA, et al. Decreased fat storage by *Lactobacillus paracasei* is associated with increased levels of angiotensin-like 4 protein (ANGPTL4). *PLoS One* 2010;5(9).
- [89] Mandard S, Zandbergen F, van Straten E, Wahli W, Kuipers F, Muller M, et al. The fasting-induced adipose factor/angiotensin-like protein 4 is physically associated with lipoproteins and governs plasma lipid levels and adiposity. *J Biol Chem* 2006;281(2):934–44.
- [90] Walton GE, Lu C, Trogh I, Arnaut F, Gibson GR. A randomised, double-blind, placebo controlled cross-over study to determine the gastrointestinal effects of consumption of arabinoxylan-oligosaccharides enriched bread in healthy volunteers. *Nutr J* 2012;11:36.
- [91] Koh A, De Vadder F, Kovatcheva-Datchary P, Backhed F. From dietary fiber to host physiology: short-chain fatty acids as key bacterial metabolites. *Cell* 2016;165(6):1332–45.
- [92] Windey K, Francois I, Broekaert W, De Preter V, Delcour JA, Louat T, et al. High dose of prebiotics reduces fecal water cytotoxicity in healthy subjects. *Mol Nutr Food Res* 2014;58(11):2206–18.
- [93] Windey K, De Preter V, Huys G, Broekaert WF, Delcour JA, Louat T, et al. Wheat bran extract alters colonic fermentation and microbial composition, but does not affect faecal water toxicity: a randomised controlled trial in healthy subjects. *Br J Nutr* 2015;113(2):225–38.
- [94] Portune KJBB, Davila AM, Tome D, Blachier F, Sanz Y. Gut microbiota role in dietary protein metabolism and health-related outcomes: the two sides of the coin. *Trends Food Sci Technol* 2016;57:213e32.
- [95] Mika A, Stepnowski P, Kaska L, Proczko M, Wisniewski P, Sledzinski M, et al. A comprehensive study of serum odd- and branched-chain fatty acids in patients with excess weight. *Obesity (Silver Spring)* 2016;24(8):1669–76.
- [96] Su X, Magkos F, Zhou D, Eagon JC, Fabbri E, Okunade AL, et al. Adipose tissue monomethyl branched-chain fatty acids and insulin sensitivity: effects of obesity and weight loss. *Obesity (Silver Spring)* 2016;24(8):1669–76.
- [97] Heimann E, Nyman M, Palbrink AK, Lindkvist-Petersson K, Degerman E. Branched short-chain fatty acids modulate glucose and lipid metabolism in primary adipocytes. *Adipocyte* 2016;5(4):359–68.
- [98] Andriamihaja M, Lan A, Beaumont M, Audebert M, Wong X, Yamada K, et al. The deleterious metabolic and genotoxic effects of the bacterial metabolite p-cresol on colonic epithelial cells. *Free Radic Biol Med* 2015;85:219–27.
- [99] Poesen R, Evenepoel P, de Loo H, Delcour JA, Courtin CM, Kuypers D, et al. The influence of prebiotic arabinoxylan oligosaccharides on microbiota derived uremic retention solutes in patients with chronic kidney disease: a randomized controlled trial. *PLoS One* 2016;11(4):e0153893.
- [100] Cho CE, Caudill MA. Trimethylamine-N-Oxide: friend, foe, or simply caught in the cross-fire? *Trends Endocrinol Metabol* 2017;28(2):121–30.
- [101] Duncan SH, Russell WR, Quartieri A, Rossi M, Parkhill J, Walker AW, et al. Wheat bran promotes enrichment within the human colonic microbiota of butyrate-producing bacteria that release ferulic acid. *Environ Microbiol* 2016;18(7):2214–25.
- [102] Benítez-Páez A, Kjølbæk L, Gómez del Pulgar EM, Brahe LK, Astrup A, Matysik S, et al. A multi-omics approach to unravelling the microbiome-mediated effects of arabinoxylan-oligosaccharides in overweight humans. *Microbiome* 2019;7 [unpublished data].
- [103] Lockyer SSA, Stanner S. Dietary fibre and the prevention of chronic disease – should health professionals be doing more to raise awareness? *Nutr Bull* 2016;41:3.
- [104] EFSA Panel on Dietetic Products NaA. Scientific opinion on dietary reference values for carbohydrates and dietary fibre. *EFSA J* 2010;8(1462).
- [105] Scientific advisory committee on nutrition of United Kingdom. Carbohydrates and health. 2015. Available at: <https://www.gov.uk/government/publications/sacn-carbohydrates-and-health-report>.
- [106] Nordic Council of Ministers. Nordic dietary surveys. 2012. Available at: <http://nordendiva-portal.org/smash/get/diva2:701738/2012>.
- [107] United States Department of Agriculture. Dietary guidelines for Americans eighth edition. 2015. Available at: [http://www.warsusdagov/SP2UserFiles/Place/80400530/pdf/0708/Table\\_3\\_NIN\\_INC\\_07.pdf](http://www.warsusdagov/SP2UserFiles/Place/80400530/pdf/0708/Table_3_NIN_INC_07.pdf). 2015.
- [108] National Health and Medical Research Council. Nutrient reference values for Australia and New Zealand. 2006. Available at: <http://www.nrv.gov.au/nutrients/dietary-fibre>.