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REVIEW

Dietary fiber in the prevention of obesity and obesity-related chronic diseases: From epidemiological evidence to potential molecular mechanisms

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ABSTRACT

Obesity is a mostly preventable diet-related disease and currently a major challenge for human populations worldwide. Obesity is a major risk factor for diseases such as type 2 diabetes mellitus (T2DM), cardiovascular disease (CVD) and certain cancers. Dietary fiber is a complex mixture of non-digestible molecules, mostly polysaccharides. Multiple epidemiological studies have demonstrated statistically significant reductions in risks of obesity, T2DM, CVD, colorectal cancer, and pre-menopausal breast cancer with higher dietary fiber intakes. Various direct and indirect mechanisms have been proposed including altered digestion and absorption, stimulation of gut hormones including glucagon-like-peptide-1 (GLP-1) and peptide YY (PYY), reduced appetite, and altered metabolism of bile and cholesterol. These may act via pathways involving G-protein-coupled receptors (GPRs), histone deacetylase (HDAC), and aromatase enzymes. Ultimately, fiber intake contributes to improving glucose levels and insulin sensitivity, lowering risk of T2DM, CVD and certain cancers. Therefore, diets rich in dietary fiber should be encouraged to prevent obesity and associated chronic disease.

KEYWORDS

Dietary fiber;
dietary fiber;
obesity;
non-communicable diseases;
microbiome;
microbiota;
short chain fatty acids

Introduction – Dietary fiber definition and its constituents

Diet plays a major role in the prevention of obesity and associated non-communicable diseases such as type 2 diabetes mellitus (T2DM), cardiovascular disease (CVD) and certain cancers World Health Organization (World Health Organization (WHO) 2019), such as colon cancer and breast cancer (National Cancer Institute 2017; National Institute of Diabetes and Digestive and Kidney Diseases 2015). There is a range of evidence from epidemiology to clinical intervention trials that suggests that dietary fiber intake lowers the risk of obesity and its related non-communicable diseases. A major challenge in reviewing the evidence is the complexity of dietary fiber components and its dietary sources. Different countries and scientific disciplines have adopted different definitions, which complicates comparison between studies.

There has been an evolution in the definition of dietary fiber, and the methodology used to analyze it for food composition data. In the UK, the British Nutrition Foundation (BNF) defines dietary fiber as "plant-based carbohydrates that, unlike other carbohydrates (such as sugars and starch), are not digested in the small intestine and so reach the large intestine or colon" (British Nutrition Foundation 2018). The European Union's (EU) define fiber "as carbohydrate polymers with three or more monomeric units, which are neither digested nor absorbed in the human small intestine" (European Commission 2020). Food Standards Australia New Zealand define dietary fiber as the "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" (Australian Government National Health and Medical Research Council 2019). This definition includes polysaccharides, oligosaccharides and lignins (Australian Government National Health and Medical Research Council 2019). The US Food and Drug Administration (FDA) defines dietary fiber as "non-digestible soluble and insoluble carbohydrates, with three or more monomeric units and lignin, that are intrinsic and intact in plants; isolated or synthetic non-digestible carbohydrates, with three or more monomeric units, determined by the FDA to have physiological effects that are beneficial to human health. Such effects include lowering blood pressure, lowering blood glucose, lowering blood cholesterol levels, increased bowel movement frequency (improved laxation), increased mineral absorption in the intestinal tract, and reduced energy intake (for example, due to fiber promoting feelings of fullness)". Finally, CODEX Alimentarius defines dietary fiber as "carbohydrate polymers with ten or more monomeric units, which are not hydrolyzed by the endogenous enzymes in the small intestine of humans, and belong

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to one of the following categories: 1) edible carbohydrate polymers naturally occurring in the food as consumed, 2) carbohydrate polymers which have been obtained from food 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". Overall, each of these definitions are similar in that they depict dietary fiber as generally originating from plant-based sources, are not digested by human enzymes or absorbed in the small intestine, and contribute positively to human health.

Furthermore, dietary fiber is often described according to its solubility in water. As such, dietary fiber can be classified as soluble or insoluble fiber. Soluble dietary fiber can hydrate in water, forming a gel-like substance within the gastrointestinal (GI) tract which increases the viscosity of GI contents and altering transit time, digestion and absorption of GI contents (Cameron-Smith, Collier, and O'Dea 1994). Soluble fibers include several types of polysaccharide including hemicelluloses (e.g., xyloglucans in fruits, vegetables and some non-cereal seeds, β-glucans in oats and barley, arabinoxylans in wheat and rice) and pectins (Evans 2020), which can be found abundantly in foods such as legumes, fruits and vegetables (Dhingra et al. 2012; Nakashima et al. 2018; Ridley, O'Neill, and Mohnen 2001). Soluble fiber also includes algae polysaccharides such as alginate and carrageenan, and gums such as guar gum and gum arabic. In the more recent US definition of dietary fiber, soluble oligosaccharides such as inulins and raffinose-like oligosaccharides would also be included. Insoluble dietary fiber, on the other hand, is the fiber that cannot dissolve or is poorly hydrated in water (Stephen et al. 2017). This type of fiber increases faecal bulk (Eggum 1995), and decreases transit time (Roberfroid 1993). Insoluble fibers are comprised primarily of cellulose, some hemicelluloses and lignins (O'Grady, O'Connor, and Shanahan 2019). Insoluble fiber is the most abundant type of fiber in most foods including legumes, fruits and vegetables, and is highly dominant in whole grains such as wheat, oat, barley and rye (British Nutrition Foundation 2018; Oldways Whole Grains Council 2020; Lunn and Buttriss 2007). The solubility of fiber is likely to impact on its fermentability, and therefore has physiological relevance. Assessment of fiber dietary intake remains a challenge. New tools are being developed to better assess fiber intake (Rijnaarts et al. 2021).

The current dietary guidelines in the UK for dietary fiber intake is 30 g/day AOAC for both females and males aged 16 to 64-years-old (British Nutrition Foundation 2018; Public Health England 2016). However, the average UK population is not currently achieving their recommended dietary fiber intake. According to the 2014–2016 National Diet and Nutrition Survey (NDNS) by Public Health England (PHE), the average dietary fiber intake of 19 to 64-year-olds was 19 g/day AOAC, with intakes of 20.7 g/day AOAC and 17.4 g/day AOAC for men and women, respectively (Public Health England 2018). Most food-based dietary guidelines recommend consuming at least 5 portions of fruits or vegetables (current average UK intake is just above 2), cereals in wholegrain form (e.g., pasta, bread, noodles) and increase intake of legumes, nuts and seeds (Gressier and Frost 2022). Major efforts in industry reformulation and the current drive toward sustainable plant-based diets should assist in increasing fiber intakes, though long term epidemiological trials are needed to evaluate the effects.

Obesity is one of the biggest and most serious public health issues currently facing the human population (World Obesity 2019; Krzysztoszek, Laudańska-Krzemińska, and Bronikowski 2019; Lee 2020). A third of the global population is now considered to be overweight or obese, a figure which has doubled since the 1980s (Chooi, Ding, and Magkos 2019). An individual is considered obese when their body mass index (BMI) is > 30 kg/m^2 (30–39.9 kg/m^2) and severely obese when their BMI is > 40 kg/m^2 (NHS 2019; Beuther and Sutherland 2007). The World Health Organization stated that 39% of adults were classified as overweight and 13% as obese in 2016 (WHO 2020). Projections to 2030 predict that 20% of the global adult population, estimated to be around 573 million people will be obese (Kelly et al. 2008). Worldwide obesity has also been seen to increase within children and adolescents. In 1975, less than 4% of children and adolescents were classified as overweight or obese. By 2016, this figure rose to 18% (WHO 2020). Furthermore, The Global Burden of Disease Study stated that, in 2017, obesity was the major cause of approximately 4.7 million premature deaths worldwide (Stanaway et al. 2018).

The etiology of obesity is complex. Typically, obesity develops as a result of an unhealthy high-energy diet (Swinburn et al. 2011), together with other lifestyle factors such as low physical activity (NHS 2019; Milagro, Moreno-Alaga, and Martinez 2020). The so called "Western" diet is a prime example of an unhealthy diet that is driving obesity and chronic disease (Manzel et al. 2014). Unhealthy diets are characterized by large portion sizes, and consumption of red and processed meats, sugar sweetened beverages, and foods high in saturated fats, added sugars, refined carbohydrates and salt (Manzel et al. 2014; Hariharan, Vellanki, and Kramer 2015), while often lacking in fiber-rich foods such as fruits, vegetables, beans, legumes, nuts, seeds, and whole grains (Harvard 2020; Birchenough et al. 2019; Chan et al. 2019). It must be noted that unhealthy dietary patterns are increasingly common across the world, and efforts to measure the extent of the nutrition transition at global level is ongoing (Singh et al. 2020). On the other hand, healthy dietary patterns to reduce obesity across geographies are also being proposed (Diotallevi et al. 2020).

Interventions to prevent or reverse obesity commonly involve dietary advice that promotes diverse diets containing a high proportion of fruits, vegetables, and other fiber-rich foods, in combination with regular physical activity (Ofei 2005). Obesity prevention is extremely important to decrease

the risk of overall mortality (Thorpe and Ferraro 2004), and also because obesity is a major risk factor for many non-communicable diseases such as T2DM, CVD, and certain cancers (Nyberg et al. 2018; Poirier et al. 2006), including colorectal cancer and breast cancer (National Cancer Institute 2017; National Institute of Diabetes and Digestive and Kidney Diseases 2015; Sung et al. 2011).

This review evaluates the epidemiological and mechanistic evidence relating to dietary fiber and the prevention of obesity and its related diseases. We focus on the overall effect of dietary fiber, rather than on individual fiber components.

Epidemiological evidence linking fiber intake to the prevention of obesity and obesity-related diseases

Fiber in the prevention of obesity

The role of dietary fiber in obesity prevention has been the subject of systematic reviews and meta-analyses. The meta-analysis conducted by Chen et al. (2017) examined 14 studies (n = 11 cross-sectional studies, n = 3 cohort studies). After removing 4 studies that showed high heterogeneity and publication bias, the analysis showed a significant protective effect of dietary fiber against metabolic syndrome risk. However, the authors concluded that there were insufficient high quality cohort studies to support the observations. Systematic review and meta-analysis of 15 viscous fiber RCTs was carried out by Jovanovski et al. (2021). The analysis suggested significant effects of viscous fiber on body weight, percentage body fat and BMI, but not weight circumference. It is clear that the effects depend on the type of fiber and the host effects. For example, a Dutch study conducted by van de Vijver et al. (2009). This study included male (n = 2,078) and female (n = 2,159) participants, aged 55 to 69-years-old, randomly selected from the Netherlands Cohort Study (NLCS) cohort. The study showed that there was a significant inverse association between wholegrain intake and BMI, as well as risk of overweight and obesity, in both men and women. However, when focusing on fiber intake, a difference between sexes was observed. For men, BMI decreased significantly by 0.04 kg/m^2 ($p < 0.01$) and 0.29 kg/m^2 ($p < 0.01$) for every 1 g/day and 1 g/MJ increase in fiber, respectively. No significant effect was observed for women. This was attributed by the authors as reporting bias, whereby women tended to under report energy dense foods which then leads to over reporting of fiber intake. A study involving Japanese women did show reduced BMIs with increased fiber consumption (Murakami et al. 2007). The cross-sectional study consisted of 3,931 Japanese female dietetics students aged 18 to 20-years-old. Self-administered questionnaires were used to collect information relating to dietary and lifestyle factors within the previous month. The study showed that higher fiber intakes were associated with lower BMI, with a difference of 0.6 kg/m^2 for participants consuming 4.3 g/4,186 kJ versus 9.0 g/4,186 kJ ($p < 0.0001$). Similar differences in BMI were observed with soluble and insoluble fiber consumption. Increases in soluble fiber from 1.1 g/4,186 kJ to 2.4 g/4,186 kJ and insoluble fiber from 3.2 g/4,186 kJ to 6.5 g/4,186 kJ were associated with a lower BMI of 0.8 and 0.6 kg/m^2 ($p < 0.0001$ for both), respectively. However, one study on a Belgian population (n = 3,083) found no association between BMI and fiber intakes but did find a statistically significant reduction in waist circumference (WC) with higher fiber intake ($p < 0.0001$) (Lin et al. 2011). In this study, gender differences in fiber intake were observed and found that gender, as well as geographical location, age and level of education, were confounding factors for the effects of fiber on measures of obesity. Overall, these findings support the hypothesis that higher dietary fiber intakes are associated with lower incidence of overweight and/or obesity, but biological and non-biological influencing factors need to be further explored.

Fiber in the prevention of T2DM

Meta-analyses have evaluated the role of fiber in T2DM prevention. One meta-analysis of 15 RCTs concluded that dietary fiber intake, through high-fiber diets or diet supplements, significantly improved several biomarkers of T2DM including fasting blood glucose and HbA1c (Post et al. 2012). Meanwhile, a meta-analysis of 23 prospective cohort studies investigated the effect of fruit and vegetable consumption on diabetes risk. It concluded that the effect may be partially attributed to fiber content in these foods (Wang et al. 2016). A meta-analysis also concluded that intake of wholegrains improved glycemic markers including fasting glucose, glycated hemoglobin (Hb1Ac) and insulin sensitivity (HOMA-IR) (Li et al. 2021). Interestingly, the study showed a higher effect of oat consumption compared to wheat and rice. Most meta-analyses show high degree of heterogeneity attributed to differences in food sources, doses and populations.

The EPIC-InterAct study conducted by The InterAct Consortium (2015) examined the link between dietary fiber intake and the incidence of T2DM in eight European countries including Germany, Denmark, Italy, France, the Netherlands, the UK, Sweden and Spain. The study involved a nested case-cohort made up of 26,088 participants obtained from the European Prospective Investigation into Cancer and Nutrition (EPIC) study cohort. The 26,088-participant cohort was made up of two groups, the sub-cohort (n = 15,258) and the incident T2DM cases (n = 11,559), with 729 of the T2DM incidence cases coming from the sub-cohort group. The results of the study showed statistically significant reductions in T2DM risk with total fiber consumption, vegetable fiber consumption and cereal fiber consumption, when adjusted for dietary and lifestyle factors. When total fiber consumption was compared between a high intake (> 26.4 g/day, median 29.7 g/day) and low intake (< 18.9 g/day, median 16.3 g/day), a reduced relative risk of T2DM of 18% was calculated ($p = 0.02$). With vegetable fiber, an intake of over 5.3 g/day (median 6.9 g/day) was estimated to significantly reduce T2DM risk by 16% when compared to daily intakes of less than 2.4 g/day (median 1.4 g/day) ($p < 0.01$). With regards to cereal fiber, a 19% reduced risk of T2DM was ascertained for a consumption of over 10.9 g/day (median 13.7 g/day) compared to the lower consumption of less

than 5.7 g/day (median 4.3 g/day) ($p < 0.01$). When fruit fiber consumption was analyzed, no significant reductions in T2DM risk were observed between the lower intake of less than 2.3 g/day (median 1.4 g/day) and higher intake of more than 6.3 g/day (median 8.4 g/day) ($p = 0.74$). However, after adjusting for BMI, none of these results for total fiber, vegetable fiber or cereal fiber were found to be statistically significant. A study conducted by Montonen et al. (2003) also showed statistically significant reductions in T2DM risk with higher consumptions of total fiber and cereal fiber when comparing higher and lower consumptions. The study was based in Finland and involved a cohort of 4,316 participants (males n = 2,286 and females n = 2,030) aged 40 to 69-years-old, similar to that of the EPIC-InterAct study cohort. None of the participants had diabetes at baseline. Like the previous study, a 10-year follow-up was done to determine the number of T2DM incidence using the nationwide register. This revealed 54 and 102 T2DM cases within the men and women, respectively. The results of the study showed a reduced risk of T2DM by 49% with the higher fiber intake quartile (33.2–118 g/day) compared to the lower intake quartile (2.6–19.2 g/day) ($p = 0.04$). However, it must be noted that the fiber intake ranges are very large. With regards to cereal fiber, a statistically significant reduction in T2DM risk by 61% was obtained when comparing higher and lower intakes ($p = 0.01$). This study showed no significant reduction in T2DM risk with fruit or vegetable fiber intake when comparing the lower intakes. The risk reductions were more pronounce in obese and older sub-sets of the cohort. It is not completely clear why no significant associations have been made between fruit/vegetable fiber and T2DM risk reduction, but have been made with cereal fiber. One explanation may be related the amounts of these foods that are habitually consumed. For example, in Montonen et al. (2003) Finnish study, participants with high intakes of cereal fiber were consuming 67.8 g/day on average compared to average fruit and vegetable fiber intakes of 3.3 g/day and 6.5 g/day, respectively. Therefore, stronger associations may be observed between cereal fiber and T2DM risk compared to fruit and vegetable fiber. The amounts of certain foods and fiber consumed in this study are much larger than in other studies and may therefore not be applicable to the other populations.

Fiber in the prevention of CVD

Several systematic reviews have investigated the effect of fiber intake on CVD risk. Systematic review and meta-analysis of 22 cohort studies showed a protective effect of dietary fiber on both CVD and coronary heart disease (Threapleton et al. 2013). Interestingly, cereal and vegetable fiber were associated with reduced risk of CVD and coronary heart disease, while fruit fiber was only associated with reduced risk of CVD. Oat has received particular attention due to the putative effects of beta-glucan on cholesterol. A meta-analysis of 8 prospective cohort studies showed a protective effect of oat consumption on T2DM and overall mortality risk, but not consistently with CVD risk (Wehrli et al. 2021). A systematic review Martínez-González et al. (2002) showed the potential role of dietary fiber in the prevention of CVD, specifically acute myocardial infarction (AMI). The study was a case-control study based within three university hospitals in Pamplona, Spain. Cases (n = 171, mean age 61.7-years-old) were matched with controls (n = 171, mean age 61.4-years-old) of the same age, gender and who were admitted to the same university hospital. In order to obtain dietary intake information, FFQs consisting of 136 different food items were completed by each participant. From which, dietary fiber intakes were split into five quintiles ranging from Q1, the lowest dietary fiber intake (median 19 g/day), to Q5, the highest dietary fiber intake (median 45 g/day). After analysis of the dietary intake data and adjustment for dietary and lifestyle factors, statistically significant reductions in first AMIs were observed, with increases in prevention as dietary fiber intake increased. Q1 (19 g/day) was used as the reference, so no reduced risk was obtained with this amount of fiber. The next four quintiles, Q2 (25 g/day), Q3 (29 g/day), Q4 (35 g/day) and Q5 (45 g/day) showed reduced risks of first AMI by 49%, 79%, 74% and 86%, respectively (test for trend $p = 0.01$) when comparing each intake quintile to Q1. This reduced risk of CVD with increased total fiber consumption supported the findings by Bazzano et al. (2003). In that prospective cohort study which included 9,776 American adults aged 25 to 74-years-old who had no history of CVD at baseline. In order to obtain dietary data, 24 hr recalls were conducted at baseline. During an average follow-up of 19 years, cardiovascular events such as coronary heart disease (CHD) and stroke, and CVD incidence were determined from participant medical records and or death certificates. The results of the study suggest that higher intakes of total dietary fiber are beneficial to reduce the risk of CHD and CVD incidence significantly, when comparing the highest intakes (> 15.9 g/1,735 kcal) to the lowest intakes (< 7.7 g/1,735 kcal). For CHD, the higher total dietary fiber intake, compared to lower intake, reduced a person's risk of incidence by 12% (p for trend = 0.05). For CVD incidence, the higher fiber intake reduced a person's risk by 11% (p for trend = 0.01). Both these statistically significant results were obtained after adjustments for various potential lifestyle and dietary confounders. This study further looked at soluble dietary fiber specifically, in terms of reduced CVD and cardiovascular event risk. The results showed that higher intakes of soluble fiber (> 4.0 g/1,735 kcal) compared to lower intakes (< 1.3 g/1,735 kcal) produced statistically significant reduced risks of CHD mortality, CVD incidence and CVD mortality by 24% (p for trend = 0.01), 10% (p for trend = 0.01) and 12% (p for trend = 0.03), respectively. Reduced risk of a similar magnitude as seen here with CVD and cardiovascular events were identified within cancer prevention with dietary fiber intake (Dahm et al. 2010).

Fiber in the prevention of colorectal and breast cancer

Systematic reviews and meta-analyses have also demonstrated reductions in the risk of both colorectal and breast cancer with higher fiber intakes. Systematic review and dose-response meta-analysis of 25 prospective studies found

a dose-dependent effect of dietary fiber, particularly cereal fiber and whole grains, in reducing the risk of colorectal cancer (RR 0.83 with an increment of three servings). The effects were weaker for total, vegetable and fruit fibers (Aune et al. 2011). The study by Dahm et al. (2010) followed a prospective nested case-control study design within seven different UK cohort studies. The study involved 579 case patients who had developed colorectal cancer and 1,996 matched control participants, aged 43 to 71.9-years-old. Dietary data was collected from each participant (n = 2,575) via food diaries and FFQs. This dietary data from both dietary methods was used to calculate the risks of developing colorectal, rectal and colon cancers. When analysis was conducted using the food diary data, the highest fiber intake (mean 24.5 g/day) compared to the lowest reference intake (mean 8.9 g/day) showed reduced risks of colon and rectal combined, colon and rectal cancers by 27%, 30% and 18%, respectively. However, none of these values were statistically significant when p for trend was tested (all $p > 0.05$). Nevertheless, analysis was also conducted on dietary fiber intake density, that is the amount of fiber per MJ of energy, to assess reduced risks of these cancers. For both colon and rectal combined, and colon cancer, statistically significant reductions of 34% (p for trend = 0.012) and 40% (p for trend = 0.014) were identified, respectively, when the highest (mean 3.0 g/MJ) and lowest (mean 1.2 g/MJ) intake densities were compared. While this analysis was also done for rectal cancer and showed a reduced risk of 16% between the highest and lowest densities, it was not statistically significant (p for trend = 0.40).

These findings were coherent with those found by Wakai et al. (2007) as reduced risks were seen for colorectal and colon cancer but not for rectal cancer alone. Wakai et al. (2007) conducted a cohort study in Japan consisting of 43,115 men and women aged between 40- and 79-years-old. Dietary data was also obtained through FFQs, from which dietary fiber intakes were calculated. An average follow-up of 7.6 years took place and from this, together with the dietary data, risks for developing colorectal, colon and rectal cancers were determined. When comparing the highest fiber intake (mean 13.4 g/day) to the lowest intake (mean 7.1 g/day) reduced risks of 27% (p for trend = 0.028) and 42% (p for trend = 0.002) for colorectal cancer and colon cancer were obtained. For rectal cancer, no statistically significant reduction in risk was observed. Therefore, corresponds to the results of Dahm et al. (2010) study and provides evidence for a link between fiber and lower colorectal cancer risk.

Wakai et al. (2007) further considered the potential of soluble and insoluble fiber in reducing the risk of these cancers. For soluble fiber, mean intakes of 2.6 g/day compared to 1.2 g/day significant reduced colorectal and colon cancer risk by 33% (p for trend = 0.022) and 45% (p for trend = 0.002), respectively. Again, no significant reduction in risk was seen for rectal cancer. The same was observed for insoluble fiber, where mean intakes of 9.6 g/day compared to 5.3 g/day reduced the risk of colorectal and colon cancer by 23% (p for trend = 0.041) and 37% (p for trend = 0.004), respectively, but not the risk of rectal cancer. However, determining the independent effects of soluble and insoluble fiber on cancer prevention is extremely difficult as they are typically consumed together and co-exist within the same foods (Dhingra et al. 2012; Khanum et al. 2000; Spiller, Amen, and Kritchevsky 1975). The lack of effect of fiber on rectal cancer may be due to low residence time in that part of the digestive system (McNeil and Rampton 1981).

Dietary fiber intake has also been shown to have a preventative role in breast cancer, although the effects are weaker compared to colorectal cancer (Aune et al. 2012). A study by Cade, Burley, and Greenwood (2007) of the UK Women's Cohort Study (UKWCS) involved 15,951 pre-menopausal women and 17,781 post-menopausal women, aged between 35- and 69-years-old, at baseline (Cade, Burley, and Greenwood 2007). As in the previous studies, FFQs were used to obtain each participant's dietary data and to calculate dietary fiber intakes. A total dietary fiber intake of at least 30 g/day compared to less than 20 g/day was seen to reduce the risk of pre-menopausal breast cancer significantly by 52% (p for trend = 0.01) but not post-menopausal breast cancer. Foods containing dietary fiber, such as cereal products and vegetables, generally contain other substances such as isoflavones and lignans (Adlercreut et al. 2000). These can be broken down into molecules know as phytestrogens. Phytestrogens have similar structures to estrogen and may compete for estrogen receptor binding sites, stopping estrogen from binding and so preventing the estrogenic pathways which can lead to pre-menopausal breast cancer (Stoll 1996). A study by Li et al. (2013) showed a significantly protective effect of fiber against breast cancer in pre-menopausal women (OR = 0.38, p for trend = 0.08) and the effect was more pronounced for prevention of estrogen receptor (ER) negative tumors. However, the effect was not observed for post-menopausal women, irrespective of ER tumor type (Li et al. 2013).

Overall, there is strong and consistent evidence provided by epidemiological trials supporting a preventative role of dietary fiber in obesity and its related diseases (Table 1).

It is important to acknowledge that epidemiological study designs can prone to bias, for example in participant selection by country or dietary pattern (The BMJ, XXXX). Therefore, caution must be exerted to avoid generalization to the global population. In particular, quite a lot of epidemiological studies focus on populations that consume high amounts of cereal wholegrains, but low amounts of fruits, vegetables, nuts and legumes. More fiber interventions are needed in a wider range of dietary contexts (Das et al. 2021).

Potential mechanisms by which fiber prevents obesity and associated diseases

As suggested by the epidemiological evidence, dietary fiber may have protective effects against obesity and its related diseases (T2DM, CVD, colon and breast cancer). Several mechanisms have been proposed which include direct effects of fiber on gut physiology with consequences on digestion,

Table 1. Reductions in the risks of the various obesity-related diseases, when comparing higher and lower total dietary fiber intakes in epidemiological studies.

Study	Disease	Mean low total fiber intake (g/day)	Mean high total fiber intake (g/day)	Reduction in risk with high vs. low fiber intake (%)	*P* for trend
The InterAct Consortium (2015)	T2DM	16.30	29.70	18.00	0.02
Montonen et al. (2003)	T2DM	10.90	75.60	49.00	0.04
Martínez-González et al. (2002)	CVD	19.00	45.00	86.00	0.01
Bazzano et al. (2003)	CVD incidence	5.90	20.70	11.00	0.01
Bazzano et al. (2003)	CHD incidence	5.90	20.70	11.00	0.05
Wakai et al. (2007)	Colorectal cancer in men	6.70	13.40	31.00	0.02
Wakai et al. (2007)	Colon cancer in men	6.70	13.40	48.00	< 0.01
Cade, Burley, and Greenwood (2007)	Pre-menopausal breast cancer	< 20.00	> 30.00	52.00	0.01

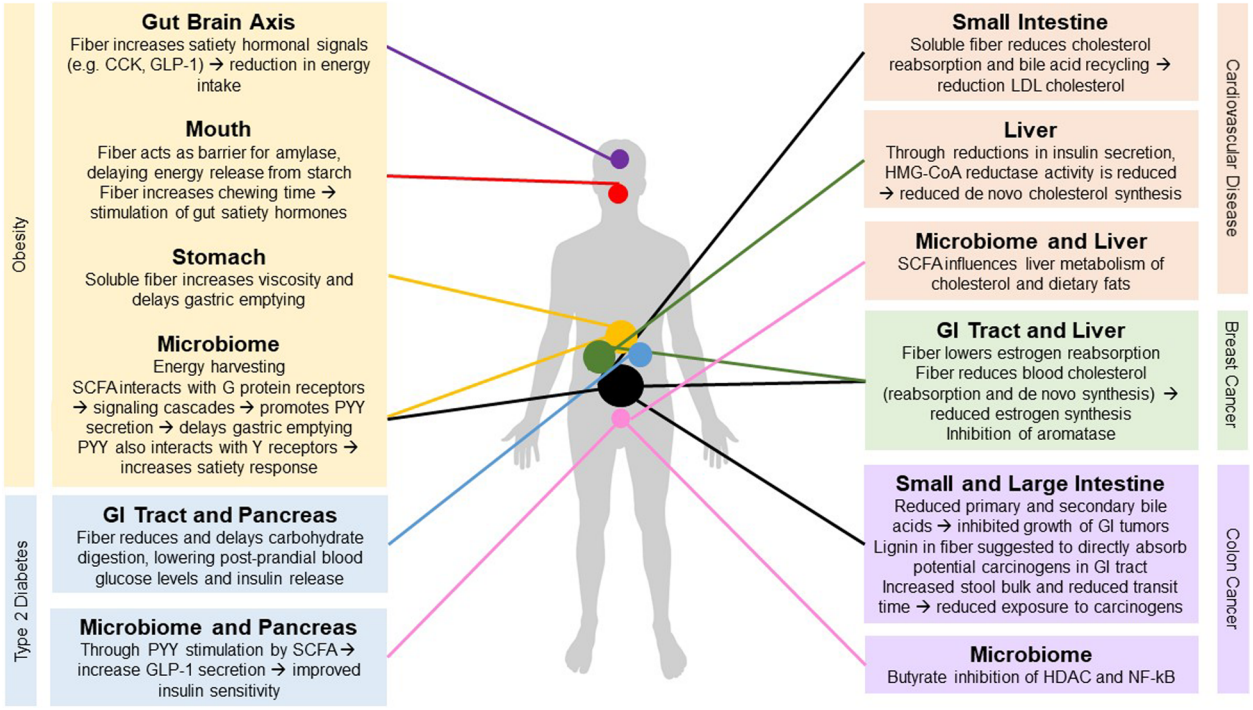

Figure 1. Diagram summarizing potential mechanisms by which fiber reduces the risk of obesity and associated diseases.

absorption and appetite; as well as indirect effects through the microbiome (Figure 1).

Direct effects of fiber on gut physiology and appetite

Obesity prevention

Lower energy intakes may help individuals achieve and regulate energy balance for weight maintenance (NICE. 2015; Church and Martin 2018). Heaton (1973) proposed three main mechanisms in which dietary fiber may reduce energy intake. The first mechanism involves the replacement of macronutrients consumed by dietary fiber. Fiber reduces energy density of foods, and therefore high-fiber diets will have lower energy content compared for the same portion size.

Secondly, foods containing fiber typically need more chewing before they can be ingested. This requirement for chewing not only slows down the rate of food consumption but also initiates feelings of satiety by stimulating the release of gut hormones, such as cholecystokinin (CCK) and glucagon-like-peptide-1 (GLP-1) (Li et al. 2011; Haber et al. 1977; Miquel-Kergoat et al. 2015; Hogenkamp and Schiöth 2013; Austin and Marks 2009; Slavin and Green 2007). As fiber increases feelings of fullness and lowers the number of calories ingested, an overall reduction in energy intake results which prevents obesity development (Astrup 2005). Moreover, soluble dietary fiber, has been specifically linked to increased feelings of satiety and a reduced overall energy intake (Adam et al. 2015; Pasman et al. 1997). Soluble fiber is thought to increase satiety by increasing viscosity of intestinal contents, producing gel-like structures, and its ability to undergo fermentation in the small intestine (Fiszman and Varela 2013).

The final mechanism suggested by Heaton (1973) is that fiber reduces the energy availability from food. For example, when comparing wholegrain products to their refined alternatives, fiber-rich cell walls act as barriers to digestive enzymes (Edwards et al. 2021; Holland et al. 2020). This "barrier" reduces the bioavailability of energy-yielding components in the GI tract (Edwards 1990). Soluble fibers increase the viscosity of the GI lumen content (Slavin and Green 2007; Dikeman and Fahey 2006), affecting digestive

enzyme activity but also slowing down the rate of gastric emptying. Together, soluble fiber can increase the duration of which satiety signals are released (Fiszman and Varela 2013). Fiber also extends oral exposure to food and generates more satiating textures (Wanders et al. 2013; Morell et al. 2014).

T2dm prevention

With regards to T2DM, increased viscosity has been shown to slow down the rate at which carbohydrates are digested and absorbed in the small intestine (Jenkins 1979; Topping et al. 1988). Fiber forms a viscous gel acting as a diffusion barrier between the epithelial cells and available glucose (Fabek et al. 2014; Flourie et al. 1984). Fiber components may also inhibit α-amylase activity (Ou et al. 2001). Altogether, this reduces the rate at which glucose is absorbed into the blood stream, and so lowers postprandial blood glucose levels (Yu, et al. 2014). As blood glucose levels are reduced, so is the release of insulin (Ludwig 1999). This may generate an overall increase in the insulin sensitivity of tissues through increased activity of insulin receptors, their subsequent tyrosine kinase pathways, and further signaling molecules (Pirola, Johnston, and Van Obberghen 2004; Song et al. 2000; Robertson et al. 2003).

CVD Prevention

Reductions in postprandial blood glucose levels by fiber have also been linked to CVD prevention (Cameron-Smith, Collier, and O'Dea 1994; Gunness and Gidley 2010). Insulin is known to promote the action of the hepatic enzyme 3-hydroxy-3-methylglutaryl-coenzyme A (HMG-CoA) reductase (Gunness and Gidley 2010; Harris et al. 2000; Istvan and Deisenhofer 2001). HMG-CoA reductase is involved in cholesterol synthesis as it increases the rate at which cholesterol is produced within the liver. It does this by acting as a catalyst for the rate limiting step of cholesterol's production (Rodwell 1976). This step involves the conversion of HMG-CoA to mevalonate (Espenshade and Hughes 2007), which undergoes further modifications producing squalene and lanosterol, before finally ending up as cholesterol (Röhrl and Stangl 2018). Therefore, inhibition of HMG-CoA reductase may result in the prevention of excess cholesterol being synthesized and released into circulation by the liver, and so may reduce the risk of atherosclerosis and so CVD (Breuer 2005; Rafieian-Kopaei et al. 2014).

The second proposed mechanism is through the inhibition of the re-absorption and recycling of bile acids (Kritchevsky 1987; Eastwood 2019; Story and Lord 1987). Some studies suggest that fiber binds to bile acids (Naumann et al. 2019), although the physico-chemical mechanisms behind this behavior are not clear.

Colorectal and breast cancer prevention

The interaction between fiber and bile may also have a role in colorectal cancer prevention. Primary and secondary bile acids, at high concentrations, have been suggested as potential carcinogens that promote the growth of tumors within the GI tract (Bernstein et al. 2005). Secondary bile acids in particular have been linked to the promotion of tumor growth (Nagengast et al. 1995) through damage to epithelial cells lining the colon, which in turn may increase the intestinal wall's susceptibility to carcinogens (Ajouz, Mukherji, and Shamseddine 2014). Additionally, secondary bile acids promote the production of reactive oxygen species (ROS), which have roles in cell proliferation and resistance to cellular apoptosis (Nguyen et al. 2018; Waris and Ahsan 2006).

Lignin, a phenolic-type of dietary fiber, has also been shown to protect against colorectal cancer development by directly adsorbing potential carcinogens within the GI tract (Ferguson and Harris 1996).

Another mechanism by which fiber may prevent colorectal cancer is through its ability to increase stool bulk (Harris and Ferguson 1993), which is seen particularly with insoluble fiber (Sloan and McRorie 2017). Increasing stool bulk can dilute potential carcinogens within the GI tract and decrease transit time (Yoon and Kim 2018). A dilution of carcinogens would reduce the likelihood of them coming into contact with the gut mucosa and epithelial cells, therefore reducing the chance of carcinogens being absorbed and or causing damage to the cells, resulting in a reduced risk of tumor formation (Masrul and Nindrea 2019). Additionally, decreased transit time reduces the probability of carcinogens coming into contact with epithelial cells (Cameron, Hardman, and Heitman 1997).

Lastly, proposed mechanisms for the prevention of breast cancer by dietary fiber involve estrogen metabolism (Rose 1992). These estrogen-related pathways are major contributors of breast cancer development (Key et al. 2003). Estrogen-related mechanisms involve the inhibition of estrogen re-absorption within the intestines (Adlercreutz et al. 1987; Lattimer and Haub 2010), as seen with bile, cholesterol, and carcinogens, and the inhibition of estrogen synthesis (Zhang et al. 2011). These mechanisms reduce estrogen levels (Rock et al. 2004; Gaskins et al. 2009), of which high levels have been linked to the development of tumors within breast tissue (Travis and Key 2003). Additionally, estrogen and their receptors are known to promote the growth and development of these breast tumors (Russo and Russo 2006; Sui, Zhang, and Fan 2011), with estrogen receptors regulating cell proliferation (Lee et al. 2012). Furthermore, the most common form of breast cancer is one that is estrogen receptor positive (Turner et al. 2017), further demonstrating evidence for estrogen's role in breast cancer. Therefore, if fiber can increase excretion of estrogen via decreased absorption (Upson et al. 2013), binding of estrogen to its receptors would be reduced, preventing the initiation of breast tissue cell growth, overall potentially reducing the risk of breast tumor development.

Finally, estrogen synthesis may be reduced by inhibition of the aromatase enzyme (Adlercreutz et al. 1993), which produces the estrogens estrone (E1) and estradiol (E2) from androstenedione and testosterone, respectively (Thomas and Potter 2013). Estrogen synthesis may also be reduced by the reductions in cholesterol levels, as previously mentioned, as estrogen can also be produced via de novo pathways from cholesterol (van Duursen 2017). Overall, these two

pathways would further decrease circulating estrogen levels, potentially preventing the development of breast cancer.

Fiber and obesity/disease prevention through Microbiome-Related mechanisms

Dietary fiber has been shown to reduce the risk of obesity and its related diseases through indirect mechanisms mediated by the microbiome (Cronin et al. 2021). The term "microbiome" is defined as "a community of microorganisms (such as bacteria, fungi and viruses) that inhabit a particular environment and especially the collection of microorganisms living in or on the human body" (Merriam-Webster 2020a). The term "microbiota" is defined as "the microscopic organisms of a particular environment" (Merriam-Webster 2020b), and is a term often used interchangeably with "microbiome" when referring to the bacteria existing within an individual's GI tract.

Fiber can alter gut microbial populations (David et al. 2014). Anaerobic fermentation of dietary fibers within the GI tract produce SCFAs amongst other products (Andoh, Tsujikawa, and Fujiyama 2003; Ríos-Covián et al. 2016; Wong et al. 2006). The interaction between fiber and microbes is complex, and likely to involve a whole range of yet undiscovered microbes, enzymes and metabolites (Cronin et al. 2021; Klassen et al. 2021). There are three main SCFAs thought to be produced by these gut bacteria; acetate, propionate and butyrate (Topping 1996). Butyrate is thought to be the major SCFA produced, providing energy to the colonocytes (Hamer et al. 2008). However, all SCFAs produced can be utilized by enterocytes in the human colon, and/or can be transported into the bloodstream via movement across the GI tract epithelium (Tan et al. 2014). While a lot of research has emphasized the roles of SCFA in obesity and disease prevention (Tan et al. 2014; Mandaliya, Patel, and Seshadri 2018), the microbiome may have other protective effects by altering the absorption of nutrients and modulation of low-grade inflammatory pathways (Baothman et al. 2016).

Obesity prevention through Microbiome-Related mechanisms

Studies have demonstrated that dietary fiber can influence obesity development through indirect mechanisms involving the microbiome. Firstly, with regards to energy intake, there has been some suggestion that obese individuals contain a microbiome made up of bacteria that are highly efficient at extracting energy from the food components entering the GI tract compared to lean individuals (Turnbaugh et al. 2006). This energy extraction process is often referred to as "energy harvesting" (Flint 2011). If that energy taken in is not expended, this would lead to weight gain and eventually could develop into obesity (Hill 2006). Evidence for this mechanism is provided by Fernandes et al. (2014) who observed that obese individuals showed significantly higher numbers of total SCFAs within their GI tract when compared to lean individuals ($p = 0.02$). This may indicate that more food material is being utilized by the gut bacteria and so may provide more energy to the host.

Studies have also demonstrated that obese individuals are seen to have increased populations of Firmicutes along with decreases in populations of Bacteroidetes (Ley et al. 2006). These changes in bacterial populations have been linked to an enhanced absorption of energy (Turnbaugh et al. 2006). However, contradictory results for this proposal were observed by both Fernandes et al. (2014) and Mariat et al. (2009), whereby no significant differences in Bacteroidetes and Firmicutes were seen between obese and lean individuals (Fernandes et al. 2014), and that moreover the ratio between these two phyla change with age (Mariat et al. 2009). This suggests that these phyla ratios are not characteristics of an obese microbiome. Additionally, Schwiertz et al. (2010) saw a significant increase in Bacteroidetes among individuals who were overweight or obese.

Contradictory evidence for these changes seen within obese individuals compared to lean individuals is further provided by the SCFAs produced via fermentation of dietary fiber. Butyrate has been shown to increase energy expenditure and is said to be protective against obesity caused by dietary factors (Gao et al. 2009). As Firmicutes are thought to predominantly produce the butyrate and Bacteroidetes are thought to produce acetate and propionate (Macfarlane and Macfarlane 2003), then increases in Firmicutes should help prevent obesity. However, Chakraborti (2015) proposed that butyrate and propionate both exerted anti-obesogenic properties, and so increases in Bacteroidetes may help prevent obesity. Furthermore, Chakraborti (2015) also postulated that acetate could promote obesity through its ability to initiate lipogenesis in the liver, suggesting that decreases in Bacteroidetes would prevent obesity. This further contradicts the initial findings of Ley et al. (2006). This lack of coherence warrants the need for further studies regarding specific gut bacteria and SCFA, and their roles in obesity. Nevertheless, other studies have been able to demonstrate other potential mechanistic pathways in which dietary fiber may indirectly prevent obesity through its microbiome-related effects.

One such final mechanism involves two G-protein-coupled receptors, GPR41 and GPR43. GPR41 and GPR43 are also referred to as FFAR3 (free fatty acid receptor 3) and FFAR2 (free fatty acid receptor 2), respectively (Wang et al. 2009). Both GPR41 and GPR43 exist on enteroendocrine cells known as L-cells in epithelial cells within the colon, in adipocytes, and in blood mononuclear cells (Ang and Ding 2016; Karaki et al. 2008; Kimura et al. 2014). SCFAs are able to bind to these receptors and generate signaling cascades involved in metabolic regulation (Ulven 2012). One of these cascades involves the secretion of peptide YY (PYY), which is a gut hormone (Bohórquez et al. 2011). PYY is is considered to be an anorectic gut hormone as it reduces appetite by delaying gastric emptying (Garattini et al. 1979; De Silva and Bloom 2012).

Evidence for the involvement of PYY was provided by studies that identified low levels of PYY in obese individuals (Viardot et al. 2008; Gueugnon et al. 2012; Brownley et al. 2010; le Roux et al. 2006). Batterham et al. (2003) demonstrated significantly low levels of PYY after fasting and after the consumption of a meal in obese individuals when

compared with lean individuals ($p < 0.001$). Therefore, dietary fiber intake would enable greater amounts of SCFAs to be produced, activating GPR41 and GPR43, stimulating the release of PYY by the L-cells, and ultimately suppressing appetite, helping to prevent weight gain.

PYY is thought to provide these anti-obesogenic effects through binding with neuropeptide Y receptors (Y1, Y2, Y4, Y5) (Yulyaningsih et al. 2011), specifically the Y2 receptor. Activations of the Y receptors prevent certain pathways, for example the degradation of cyclic AMP (cAMP) (Larhammar 1996). cAMP is a very important molecule involved in metabolism as it can promote glycogenolysis and lipolysis within muscles and adipose tissue, respectively (Sutherland and Robison 1969). Therefore, encouraging the body to use up stored energy, which may help to prevent obesity.

Additionally, the Y2 receptor, along with other Y receptors, are present within areas of the brain, such as the hypothalamus which also have crucial functions in regulating metabolism (Fetissov, Kopp, and Hökfelt 2004). The hypothalamus helps to control appetite by receiving and relaying central and peripheral pathway signals (Suzuki et al. 2010). One peripheral pathway is the binding of PYY to Y2 receptors located on vagal afferent nerve terminals (Ueno et al. 2008). Here, pro-opiomelanocortin neurons located within the arcuate nucleus get activated, stimulating these satiety signals and generating decreases in appetite (Heisler and Lam 2017). Thus, aiding in the prevention of weight gain and so possibly obesity.

Multiple studies have suggested gender specific microbiome dysbiosis with effects on obesity and health outcomes (Kim et al. 2020{Haro, 2016 #327]}.

T2dm prevention through Microbiome-Related mechanisms

Both GPR41 and GPR43 are thought to have a role in T2DM as well as obesity. Both GPR41 and GPR43 have demonstrated roles in the regulation of glucose homeostasis and pancreatic ß-cell insulin release (Swaminath 2008), on binding with the SCFAs (Ulven 2012). This binding generates signaling cascades involving not only the release of PYY, as seen in the previous obesity section, but also the release of GLP-1 by enteroendocrine L-cells (Cani, Everard, and Duparc 2013). These molecules may also exert anti-diabetic properties (Li et al. 2017), as well as the anti-obesogenic previously mentioned.

GLP-1 stimulates the release of insulin by the pancreatic ß-cells and inhibits the secretion of glucagon (Zhang et al. 2017; Müller et al. 2019). This enables rising blood sugar levels to be lowered back to normal baseline levels (Meier 2012). Therefore, an increased dietary fiber intake generates an increase in beneficial bacteria, leading to an increase in SCFA production and ultimately enhanced activation of GPR43. This enables improved pancreatic ß-cell activity and greater insulin production, generating an overall improvement in blood glucose homeostasis within individuals with T2DM.

Evidence for the activation of GPR41 and GPR43 by SCFAs, specifically acetate, propionate, and butyrate, was provided by Brown et al. (2002) and by Le Poul et al. (2003). Le Poul et al. (2003) further demonstrated that each of these SCFAs exerted different levels of efficacy for each receptor. It was seen that propionic acid was the most effective SCFA at activating both GPR41 and GPR43. Butyrate followed propionate in effectively activating GPR41 and was more effective when compared to acetate. Acetate then followed propionate in effectively activating GPR43 and was more effective when compared to butyrate (Le Poul et al. 2003).

This evidence has resulted in the consideration for GPR41 and GPR43 as possible targets for drug therapies in T2DM and obesity (Ang and Ding 2016; Rayasam et al. 2007; Ichimura et al. 2014).

CVD Prevention through Microbiome-Related mechanisms

The SCFA propionate is thought to exert a protective effect against CVD. Propionate appears to play a role in the regulation of cholesterol production in the liver (Ooi and Liong 2010). Wright, Anderson, and Bridges (1990) also reported a possible role in preventing the synthesis of fatty acids. These effects were also observed by Chen, Anderson, and Jennings (1984) in an animal study whereby the rats fed a propionate enriched cholesterol diet had significantly lower cholesterol levels within their blood and liver compared to those fed diets without propionate. The mechanism by which propionate is thought to achieve this is through its ability to block the utilization of acetate for the synthesis of cholesterol (Wolever, Spadafora, and Eshuis 1991). Acetate is used to make acetyl-coenzyme A (Acetyl-CoA) in the liver, which is a precursor for cholesterol biosynthesis, involving HMG-CoA reductase as a rate limiting step (Park et al. 2018). However, a later study conducted by Wolever et al. (1995) saw no significant effect of propionate on cholesterol levels but did observe some evidence to suggest its role in the prevention of acetate utilization in lipid synthesis. Furthermore, the mechanisms by which propionate is able to prevent cholesterol and lipid synthesis remain unclear, with other studies showing conflicting evidence against it. For example, Hara et al. (1998) found that it may actually be the SCFA acetate, also produced during the anaerobic fermentation of dietary fibers, that has the ability to reduce blood cholesterol levels rather than propionate.

Colorectal cancer prevention through Microbiome-Related mechanisms

A role for SCFA butyrate in the prevention of colorectal cancer has been proposed, mainly through its ability to induce apoptosis and prevent proliferation of cancer cells (Clausen, Bonnén, and Mortensen 1991). However, there is thought to be a paradox called the "butyrate paradox" as butyrate is seen to cause proliferation among normal healthy colonic cells whilst at the same time preventing growth and proliferation of colonic cancer cells (Scheppach, Bartram, and Richter 1995). In terms of colon cancer prevention,

butyrate is thought to achieve this through effects on the immune system pathways, whereas its role in bowel cancer prevention is thought to be through inducing apoptosis within cancer cells by preventing the activity of histone deacetylase (HDAC) enzymes (Chen and Vitetta 2018).

With reference to butyrate's effects on the immune system for preventing colon cancer, this mechanism is believed to involve the butyrate G-protein-coupled receptor GPR109A (Singh et al. 2014). In colon cancer, this receptor is essentially switched off but on binding with butyrate is able to be switched back on. This activation on binding with butyrate enables apoptosis to occur within colon cancer cells through modulation of for example Bcl2. The action of nuclear factor kB (NFkB) is also prevented by the binding of butyrate with GPR109A. However, this occurs in both the colon cancer cells and the normal healthy colonic cells (Thangaraju et al. 2009). NFkB is an important molecule within the regulation of immune responses and inflammation as it is as a transcription factor (Dolcet et al. 2005). NFkB is also specifically associated with proinflammatory cytokines, thus promoting inflammation (Schottelius and Baldwin 1999). Therefore, if its activity is prevented by butyrate and GPR109A binding, and GPR109A being thought to act as an anti-inflammatory itself, then protection against both overall colon cancer development and colon cancer initiated by inflammation is enhanced (Elangovan et al. 2014).

A second mechanism involving butyrate in cancer prevention is via the inhibition of HDAC enzymes. This preventative effect is thought to be due to HDAC inhibition generating the promotion of the tumor suppressor gene p21, which enables even greater inhibition of cyclin-D kinases (CDK) (Hassig, Tong, and Schreiber 1997). As CDK4 and CDK6 are known to encourage the proliferation and growth of cells through the advancement of the cell cycle, their inhibition is important in preventing the growth and development of cancerous cells and stopping their progression to tumors (Musgrove et al. 2011).

Lastly, this inactivation of HDAC enzymes by butyrate has also been seen to prevent inflammation and growth of colon cancer cells by altering and preventing the pathways involving the activation of the transcription factor NFkB within these cancer cells (Place, Noonan, and Giardina 2005). This is thought to be the case as NFkB aids in the formation, growth, and survival of tumors via the promotion of cell proliferation and resistance to apoptosis (Park and Hong 2016; Karin et al. 2002; Nakajima and Kitamura 2013), as previously mentioned. Therefore, both HDAC and NFkB inhibition by the presence of butyrate, as a result of dietary fiber consumption, would help to prevent the development and progression of colorectal cancer.

General conclusions

Overall, this review has found evidence from both epidemiologically and mechanistic studies, that dietary fiber intake may protect against obesity and its related chronic diseases.

A harmonized international definition of dietary fiber, together with improved tools for fiber intake assessement, are needed to consolidate dietary fiber's role in disease prevention. This would ensure that studies conducted globally, whether epidemiological or interventional, would be expressing fiber and its components, in a comparable way. This in turn would generate a robust body of evidence to justify, ascertain, and strengthen the associations between dietary fiber intakes and disease prevention.

Furthermore, dietary intervention trials in a wide range of dietary contexts are required to reduce selection bias. Dietary trials with clearly defined high-fiber diets, or well characterized dietary fiber supplements are also needed. This enable the elucidation of effects of specific dietary fiber components to be understood.

Finally, although this review addresses obesity and its related diseases separately, the mechanisms clearly demonstrate their disease pathways are somewhat interlinked. The same enzymes, hormones, receptors and or pathways are often affected, and one disease and/or risk factor often leads to the development of another, as is often seen in people with metabolic syndrome. Individual responses to diets, for example by gender and ethnicity, as well as the interaction of fiber with other dietary components, need to be further elucidated. It is worth noting that fiber-rich foods are also often rich in bioactive phytochemicals. These compounds may also show protective effects against obesity and associated diseases (Diotallevi et al. 2020; Bordoni et al. 2019).

To conclude, there is strong evidence to suggest a role for dietary fiber in the prevention of obesity and its related diseases, with further research required to substantiate the evidence in a range of dietary contexts and to fully understand the mechanisms involved. This could then inform nutrient and food-based dietary guidelines for consumers, as well as guide industrial formulations of higher fiber products.

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