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Review Article

Dietary Fiber, an Overlooked Macronutrient for Optimal Health

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Abstract

Dietary fiber is a vital macronutrient for humans and provides numerous health benefits, such as lowering blood glucose and cholesterol levels, reducing cardiovascular disease risk, and enhancing gut health. Dietary fiber remains intact in the upper digestive system and interacts with food chyme during digestion. These interactions include volume expansion, increased viscosity, and reduced nutrient absorption. This promotes satiation and reduces food intake. Fiber also slows stomach and small intestine emptying, enhancing satiety, and helping to regulate blood sugar and cholesterol levels. In the colon, water-soluble dietary fiber ferments via gut microflora, producing metabolites with additional health benefits. Fermentation is crucial in maintaining gut health and has systemic effects on overall human health. However, dietary fiber consumption remains significantly below recommended levels, averaging only 50% of the advised intake. This review aims to elucidate the types, properties, benefits, and regulatory landscape of dietary fiber to encourage greater consumption.

Keywords: Dietary Fiber; Macronutrient; Biological Function; Viscosity; Fermentation; Short-Chain Fatty Acids

Introduction

Dietary fiber is an essential macronutrient in a healthy diet [1-5]. A diet low in dietary fiber coincides with the growing global prevalence of obesity, which has tripled over the last half-century [6-9]. Based on data from 2022, obesity and overweight affect an estimated 850 million and 2.5 billion people, respectively [10,11]. Low fiber intake is also a significant contributor to chronic illnesses, including Type 2 Diabetes Mellitus (T2D), dyslipidemia, hypertension, obstructive sleep apnea, and Cardiovascular Disease (CVD) [12]. Reversing these trends requires lifestyle changes, primarily through dietary modification [13,14].

Dietary fiber reduces the risk of developing conditions associated with increased levels of glucose and cholesterol, including obesity, CVD, cancer, and diabetes [15-20]. Digestive enzymes cannot break down dietary fiber and pass it undigested through the upper gastrointestinal (GI) tract. However, dietary fiber can aid in the emptying of the upper GI tract and regulate the absorption of sugar and cholesterol in the intestine, helping to control hunger, blood sugar, and cholesterol levels [2,15,21,22]. Soluble Dietary Fiber (SDF) is fermented and utilized by microbes in the large intestine, affecting microbial growth and the microbiome environment in the large intestine [23-25]. Dietary fiber may benefit the gut microbiome through anti-inflammatory effects that alleviate chronic inflammation and associated conditions, such as chronic constipation [23,26]. Nonfermented dietary fiber's water absorption and bulking effect in the large intestine may also help with chronic constipation [27,28].

Recommendations for daily dietary fiber intake vary globally. The World Health Organization (WHO) and the European Food Safety Authority (EFSA) recommended 25 g/day of naturally occurring dietary fiber for bowel function, reduced risk of CVD and T2D, and improved weight maintenance [29,30]. The current Dietary Guidelines for Americans recommend 14 g dietary fiber per 1,000 kcal/g based on the observation of CVD risk reduction with increased fiber intake and progression of diet-related chronic diseases associated with fiber-poor diets [31].

Dietary fiber intake in Europe is significantly below recommended levels [32]. Despite observational studies showing an association between dietary fiber and reduced health risks, intake has not changed considerably over the past 20 years [33]. This gap continues despite health promotion organizations encouraging dietary fiber intake for disease prevention and management and efforts to increase the consumption of fiber-rich foods such as whole grains, legumes, nuts, fruits, and vegetables [33]. In the U.S., dietary fiber intake levels are also below recommendations [33]. A typical diet in the U.S. contains an average of 8.1 g of dietary fiber for every 1,000 calories, or 58% of the recommendations, as reported in a 2017 survey by the U.S. Department of Agriculture (USDA) [33]. Inadequate dietary fiber intake is associated with the onset and/or progression of diet-related chronic diseases and is considered a public health concern of the general U.S. population [31].

The nutritional gap in dietary fiber intake, along with the pandemic-related increases in obesity and associated chronic diseases, has prompted renewed interest in the relationship between dietary fiber intake and human health [34]. The USDA has a recommended diet pattern that provides adequate dietary fiber intake. The dietary fiber intake gap is widened by the Western diet patterns, where fruits, vegetables, and whole grains are under-consumed by more than 85% of adults [31]. Addressing the deficiency of dietary fiber in the diets of industrialized populations requires a multi-faceted approach. Besides lifestyle changes, dietary advice, and education, there is a critical need for easier access to dietary fiber sources in the diet [22,35].

In this review, we focus on the definition, properties, and benefits of dietary fiber, a macronutrient that has not received as much attention as its more prominent counterparts, protein, sugar, oil, and fat. Our objective is to explore the current literature on dietary fiber's properties and health benefits, particularly emphasizing its metabolic functions in the upper GI tract and large intestine, its impacts on microbiota, and its overall effects on human health. Additionally, we will cover a variety of global regulations on fiber supplement products.

Dietary Fiber Defined

The definition of dietary fiber varies among regulatory agencies and scientific organizations in different countries. Dietary fiber is generally defined by the specific fiber's enzyme resistance properties and health benefits [36]. The Codex Alimentarius Commission 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 [36]. The Codex further categorizes dietary fiber into several types: edible carbohydrate polymers naturally occurring in food as it is consumed; carbohydrate polymers obtained from raw food material by physical, enzymatic, or chemical means that have

a physiological benefit to health as demonstrated by generally accepted scientific evidence to competent authorities [36]. The Codex also clarifies that dietary fiber from plant origin may include fractions of lignin and other compounds associated with polysaccharides in plant cell walls [36]. Lignin is not a qualified dietary fiber if the compounds are extracted and reintroduced as a food ingredient [36]. The Codex officially accepts degrees of polymerization (DP) of ten or more for carbohydrates to be classified as dietary fiber. Still, it allows for a DP between 3 and 9, depending on individual countries' regulations [36].

The Codex definition also requires derived or synthetic carbohydrates to show a physiological benefit to human health for classification as a dietary fiber [36]. Still, it does not describe those benefits, and they are demonstrated by generally accepted scientific evidence to competent authorities [36]. Various benefits have been demonstrated with different levels of evidence by academia, institutes, and agencies worldwide [37]. These include reduced blood total and/or Low-Density Lipoprotein (LDL) cholesterol levels, increased fecal bulk/laxation, attenuation of postprandial glycemia/insulinemia, positive modulation of colonic microflora, reduced blood pressure, increased satiety, weight loss or reduction in adiposity, increased colonic fermentation and Short-Chain Fatty Acid (SCFA) production, and decreased transit time.

The U.S. Food and Drug Administration (FDA) defines dietary fiber as two types of non-digestible carbohydrates consisting of three or more sugar molecules (DP $\geq$ 3): 1) naturally occurring fibers that are intrinsic and intact in plants, including both soluble and insoluble carbohydrates and lignin; and 2) isolated or synthetic non-digestible carbohydrates that have been specifically evaluated and determined by the FDA to have beneficial physiological effects on human health [38]. The list of isolated or synthetic fibers approved by the FDA is growing. Currently, it includes β-glucan soluble fiber, psyllium husk, cellulose, guar gum, pectin, locust bean gum, hydroxypropyl methylcellulose (HPMC), mixed plant cell wall fibers, arabinoxylan, alginate, inulin and fructans, type 2 resistant starch (RS2), cross-linked phosphorylated resistant starch type 4 (RS4), glucomannan, and acacia (gum arabic) [39,40]. Dietary fiber has very different monomer types, glycosidic linkages, and side chains, which makes dietary fiber a complex family of chemicals [41].

Properties of Dietary Fiber

Dietary Fiber: Characterization and Measurement

Human digestive enzymes for carbohydrates include sucrase, glucosidase, lactase, maltase, trehalase, amylase, and chitinase [42,43]. Utilizing the enzyme-resistant properties of dietary fiber, enzymatic gravimetry methods were developed to determine dietary fiber content using the Association of Official Analytical Chemists (AOAC) Official Methods of Analysis (OMA) 991.42,

991.43, 993.19 and American Association of Cereal Chemists International (AACCI) (now Cereals & Grains Association) approved methods of 32-05.01, 32-07.01 [44,45]. Amylase and glucosidase are used to treat fiber samples to break down digestible carbohydrates into simple saccharides and measure long-chain carbohydrates insoluble in an 80% (v/v) water-ethanol solution. These methods are suitable for high DP dietary fibers (DP > 10). For low molecular weight dietary fibers (DP < 10), gel permeation chromatography methods are needed using AOAC OMA 2011.25, 2009.01, 2001.03, and AACC (American Association of Cereal Chemists) approved methods of 32-41.01, 32-45.01, and 32-50.01. The chain length or DP and the amount of side chains determine dietary fiber's physical and chemical properties, including water solubility, viscosity, and microbial fermentability, which are linked to the physiological effects of dietary fiber.

The viscosity of dietary fiber is proportionally related to its average DP [46]. As the molecular weight and interactions between carbohydrate chains increase, viscosity increases, while the solubility decreases and eventually diminishes [46]. The extended contact between the long molecular chains of viscous dietary fiber with water and digested food leads to enhanced intermolecular attractions that contribute to flow resistance. This results in the viscous gel-forming and bulking properties of dietary fiber in the digestive tract. For a given molecular weight, a branched dietary fiber chain will have a smaller volume and, hence, reduced viscosity than a linear chain fiber. Viscosity is commonly measured in two ways: absolute and kinematic viscosity. Absolute viscosity is typically expressed in millipascal-seconds (mPa s) or centipoise (cP), with 1,000 mPa s being equal to 1,000 cP or one pascal-second (Pa s). Kinematic viscosity, on the other hand, is calculated by dividing the absolute viscosity by the fluid's density, and it is measured in square meters per second (m²/s). Food mixture exhibits a complex non-Newtonian fluid behavior, and its apparent viscosity depends on shear rate and concentration. No standardization exists regarding viscosity measurement in nutritional sciences, making inferences and comparisons among studies difficult. Due to the confusion surrounding the various methodologies for measuring viscosity, establishing standardized guidelines for conducting proper measurements is critical to ensure continued sound scientific research on how viscosity affects dietary fiber and nutrition [47].

SDF is more likely to be utilized by microbes in the large intestine through fermentation compared with insoluble dietary fiber [48]. When SDF enters the colon through the small intestine, gut bacteria degrade SDFs into oligosaccharides (DP < 10), monosaccharides, SCFAs, and other chemicals through different degradation systems. These breakdown products can act as an energy source when absorbed by the body, and they influence the biological environment within the large intestine. When fermented, SDF starts to lose its water absorption and viscous properties. The gut microbes contain a diversity of carbohydrate-active enzymes, which provide flexibility to the microbiota to switch between different fiber energy sources [43].

Low molecular weight dietary fiber or oligosaccharides (DP < 10) can be readily fermented and utilized by gut microbes [49]. The gas generation from fermentation and GI tolerance is a concern [50]. Not all fibers have the same GI tolerance; for example, oligosaccharides can cause symptoms with low doses (10 g), while other fibers have been consumed at doses up to 50 g without symptoms [50]. The Fermentable Oligosaccharides, Disaccharides, Monosaccharides, and Polyols (FODMAP) diet was developed due to the association between consumption of fermentable short-chain carbohydrates and symptom induction in those with functional bowel disorders (FBDs) [50]. The pooled global prevalence for FBDs was recently shown to be as high as 33.4% [51]. FODMAPs may also worsen visceral hypersensitivity, inducing bloating, pain, and discomfort via various peripheral factors, such as altered microbiota, increased intestinal permeability, and activated immune/inflammatory response. FODMAPs contribute to quick colonic gas production through fast fermentation, which may cause bloating and abdominal pain in those with visceral hypersensitivity [50]. Excessive gas production can also cause faster colonic transit in those with IBS-D due to colonic sensitivity to increased intestinal volume [52]. Intestinal irritation can increase luminal water and may contribute to diarrhea [53]. A low FODMAP diet results in a 50% to 80% reduction of IBS symptoms [54]. It is advised that total FODMAP content should be around 2.5 to 3 g per day, while a typical Western diet ranges from 15 to 30 g per day of total FODMAPs [54].

Dietary Fiber: Types and Sources

In the U.S., the FDA approval process for a dietary fiber to be included in the Nutrition and Supplement Facts label consists of an evaluation to determine if the fiber provides beneficial physiological effects on human health [39]. The process begins with submitting scientific evidence by citizen petitions, demonstrating that a fiber has specific health benefits, such as lowering blood glucose or cholesterol levels, or improving bowel function [40]. The FDA reviews the published scientific evidence to ensure it is robust, reliable, and based on well-conducted research. If the fiber meets these criteria, the FDA will officially recognize it as a dietary fiber for nutrition labeling purposes, allowing it to be listed as a dietary fiber on food product labels. A list of the qualified dietary fiber and their functions was published and updated by the agency, see Table 1 [39,40].

Fiber	Chemical Nature	Function (FDA Approved)	Molecular Weight	1% Viscosity	Dose, g
Acacia gum	arabino β-1,3 galactan	Blood glucose	900 kDa	1,000 cP	5 to 20
Konjac gum	gluco β-1, 4 mannan	Blood lipid, defecation	1,000 kDa	18,000 cP	1 to 15
Guar gum	galacto β-1,4 mannan	Blood glucose, cholesterol	1,000 kDa	40,000 cP	15 to 30
Locust bean gum	galacto β-1,4 mannan	Blood cholesterol, bile acid secretion			8 to 25
Psyllium husk	arabino β-1,3 and1,4 xylan	Coronary heart disease	1500 kDa	1,000 cP	> 7
Arabinoxylan	arabino β-1,4 xylan	Fasting, prandial blood sugar			3 to 15
β-glucan (oat)	β-1,3 and -1,4 glucan	Coronary heart disease	500 kDa	1,000 cP	3 to 10
Pectin	α-1,4 galacturonan	Blood cholesterol	50-150 kDa	400 cP	9 to 36
Alginate	β-mannuronan co α-glucuronan	Blood sugar, insulin	30-400 kDa	100-10k cP	2 to 15
Inulin	β-2,1 fructan	Calcium absorption	<15 kDa	Low	3 to 44
GOS	β- 1,4 and -1,6 galactan	Calcium absorption	2 kDa	Low	5 to 20
Resistant starch 2/4	α-glucose, type II, IV (synthetic)	Calcium, blood glucose, energy intake		Low	25 to 40
Cellulose	β-1,4 glucan	Laxative	600 kDa	Crystalline	
HPMC	β-1, 4 glucan	Cholesterol	90 kDa	100 cP	5 to 15
Polydextrose		Energy intake (satiation)	80 kDa		10 to 30

Abbreviations: cP, centipoise; GOS, Galactooligosaccharides; HPMC, Hydroxypropyl Methylcellulose; MW, Molecular Weight

Table 1: U.S. FDA approved dietary fiber types and properties.

Alginate is an unbranched binary copolymer of β-1,4 mannuronic acid and α-1,4 guluronic acid of widely varying composition and structure [55]. Alginates contain homopolymeric blocks of contiguously linked mannuronic acid (M-blocks), alternated by guluronic acid (G-blocks) sequences, and mixed GM-blocks can also occur along the polymer chain [56]. Alginate can be extracted from various species of brown algae, such as *Ascophyllum, Durvillaea, Ecklonia, Laminaria, Lessonia, Macrocystis, and Sargassum*, as the calcium, magnesium, and sodium salts of alginic acid. The uronic acid polymer is not water-soluble in its acidic form but becomes soluble when it forms a salt with sodium or potassium. Cations with multiple charges and polycations will significantly reduce alginate's solubility, which could contribute to the excretion of heavy metals in feces. Alginates have a wide range of molecular weights, which can be between 200 kDa and 1,000 kDa, and vary with biosynthesis and degree of depolymerization during extraction. Alginate has a beneficial physiological effect on postprandial glucose levels, as reviewed by the FDA [39].

Arabinoxylan is a type of hemicellulose and a key component of the cell walls of cereal grains [57]. It is a diversely composed β-1,4 xylan polymer that contains arabinose and various uronic acid side branches [56]. Psyllium husk, the milled seed coat removed from the psyllium seed, is a concentrated source of the soluble fiber arabinoxylan [58]. Arabinoxylan is found in the alkali-soluble fraction of psyllium husk and is thought to be the active component of psyllium husk. Psyllium gum consists of a highly branched acidic arabinoxylan structure with a very high molecular weight of approximately 1,500 kDa, contributing to its limited solubility in water. When dispersed in water, it swells and forms a mucilaginous dispersion with gel-like properties. Strong evidence indicates that arabinoxylan has a beneficial physiological effect on blood glucose and insulin levels [57]. Psyllium husk qualifies as dietary fiber because research has demonstrated its effectiveness in reducing the risk of coronary heart disease (CHD) [38]. Arabinoxylan is qualified as dietary fiber for its blood glucose reduction and insulin level benefit as reviewed by FDA [39].

The structural intricacies of β-glucan molecules reveal wide variations depending on their origin. β-glucan has garnered recognition as a bioactive food ingredient due to its diverse biological activities [59]. It is found in various sources, including bacteria, algae, barley, yeast, mushrooms, and oats. Primary dietary fiber sources for β-glucan include cereals like oats, barley, sorghum, wheat, and rye. Among these, oats and barley share a distinctive molecular arrangement of β-D-glucose units connected by alternating (1→3) and (1→4) linkages [59]. The β-glucan content can vary from cultivar to cultivar under specific environmental conditions. Typically, oats contain 6% to 8% and barley 4% to 10% (w/w) β-glucan [59]. Studies have shown that the molecular weight of oat and barley β-glucans ranges from 130 kDa to 390 kDa and 190 kDa to 410 kDa, respectively.

Some mushroom varieties, such as oyster and shiitake, are good β-glucan sources. Mushroom cell walls are rich in long- or short-chain polymers of glucose subunits with β-1,3 and β-1,6 linkages responsible for β-glucan's linear and branching structures [59]. For instance, mushroom-derived β-glucans typically feature short β-1,6 linked branches, while yeast-derived counterparts exhibit β-1,6 side branches and additional β-1,3 regions. The molecular weight of β-glucan directly influences its viscosity through its water retention properties and solubility. This property has significant implications for human health, as the viscosity of β-glucan affects its ability to lower cholesterol, regulate blood glucose levels, and support immune system function in the digestive tract. The FDA has approved β-glucan from oat and barley as a dietary fiber based on its role in reducing the risk of CHD [38].

Cellulose is the major structural polysaccharide in plant cell walls and is widely present in vegetables, fruits, and cereals [60]. It is a high molecular weight linear homopolymer of β-1,4 glucose monomers [56]. Every second residue is rotated 180°, which enables the formation of intermolecular hydrogen bonds between parallel chains. The numerous intermolecular H-bonds and van der Waals forces produce a three-dimensional fibrous crystalline bundle. Cellulose is highly insoluble and impermeable to water and is, therefore, not fermentable by colonic microbes [61]. The FDA has approved cellulose as a dietary fiber on the nutrition label based on its effectiveness in improving laxation [38].

Fructans, oligosaccharide compounds with demonstrated physiological benefits, occur naturally in select monocotyledonous and dicotyledonous plant taxa, including asparagus, garlic, leek, onion, Jerusalem artichoke, and chicory root [62]. Fructan is a naturally occurring polysaccharide that contains mainly β-2,1 fructose linkage with possible terminal glucose linked through α-1,2 glycosidic bond. Inulin is among the most extensively studied fructans and is a mixture of fructan polymers with a DP ranging from 3 to 60 [63]. Oligofructose is a shorter-chain fructan that can be extracted from plants or enzymatically synthesized, referring to fructans with a DP < 10, and accounts for approximately 30% of the total inulin present in chicory root extract [64]. These linkages can be fermented by microorganisms in the colon. While inulin is a soluble fiber, it lacks the typical properties of other soluble long-chain dietary fibers, such as viscosity [65]. Evidence supports that inulin-type fructans extracted from chicory root, as well as those from different sources and synthetic inulin-type fructans, have a beneficial physiological effect on bone mineral density and calcium absorption; and inulin and inulin-type fructans were added to the FDA's list of approved dietary fibers [39].

Galactomannan is the second-largest storage polysaccharide group in many plant seeds' endosperm or cell walls [56]. Galactomannan is a linear polymer of β-1,4 linked mannose monomers with galactose residues linked through β-1,6 bonds, forming short side

branches. Guar gum, obtained from guar plant seeds, and locust bean gum, from locust bean seeds, are two sources of galactomannan fiber [66]. Locust bean gum generally has an average mannose-to-galactose ratio of about 3.5, the highest among commercially available galactomannans, such as guar gum (1.8) and tara gum (3.0). Locust beans, guar, tara, and cassia gums are manufactured commercially. Isolated galactomannan is hydrophilic, viscous, and has gel-forming properties [66]. The FDA approves this fiber for attenuating blood cholesterol levels and is therefore considered a dietary fiber for nutrition labelling [39].

Glucomannan is a soluble, highly viscous fiber commonly derived from the root of amorphophallus konjac [67]. Glucomannans are linear polymers of both β-1,4 mannose and β-1,4 glucose residues. The basic structure of konjac glucomannan (KGM) consists of glucose and mannose residues in a molar ratio of 1:1.6 to 1.7, polymerized by β-1,4-pyranoside bonds and has a DP up to 6,000 [68]. The glucose and mannose units are linked by β-1,4 glycosidic bonds with occasional acetyl groups at the C-6 position of the sugar units. Acetyl groups scattered randomly along the glucomannan backbone contribute to its water solubility. Konjac glucomannan is a high molecular weight polymer (>300 kDa) that can form viscous pseudoplastic solutions. Glucomannan can lower cholesterol, triglyceride, and glucose levels and may promote weight loss [68]. It demonstrates a beneficial effect on attenuating blood cholesterol levels when taken in doses of 2 to 13 g/day and is considered a dietary fiber for nutrition labeling [39].

Gum acacia, or gum arabic, is a biopolymer consisting of arabinose and galactose monosaccharides, a natural exudate harvested from the acacia tree [69]. The gum is an arabinogalactan protein complex, primarily composed of calcium, magnesium, and potassium salts of arabic acid [69]. The main chain of this polysaccharide is built from β-1,3 and 1,6 galactopyranosyl units, along with β-1,6 glucopyranosyl uronic acid units [56]. Its side branches may contain α-rhamnopyranose, β-glucuronic acid, β-galactopyranose, and α-arabinofuranosyl units with 1,3, 1,4, and 1,6 glycosidic linkages. Arabic acid mainly consists of β-1,3 galactose with 1,6 glycoside-linked side chains of two to five β-1,3 galactose. The fundamental chain and the branches contain arabinose, rhamnose, glucose, and methyl glucose residues. This polymer's highly branched molecular structure and relatively low molecular weight are responsible for these properties. Available scientific evidence supports the beneficial physiological effects of gum acacia on postprandial blood glucose and insulin levels, and it is considered a dietary fiber for nutritional labelling [39].

HPMC is a synthetic propylene glycol and methyl ester of cellulose, containing methyl groups and hydroxypropyl groups [70,71]. HPMC contains both hydrophilic and hydrophobic groups, behaves as an emulsifier, and is commonly utilized as a film former, stabilizer, and thickener in the food and supplement industries. It meets the definition of dietary fiber for food labeling

due to its effect on attenuating blood cholesterol levels [39].

Pectin is present in the cell walls and intracellular tissues of fruits and vegetables [56]. While pectin is abundant in fruits, it is also found in vegetables, legumes, and nuts. Pectin polysaccharides are copolymers of α-1,4 galacturonic acid units with α-1,2 rhamnose residues in adjacent or alternate positions. Pectin is highly heterogeneous in its molecular weight and chemical structure. Pectin is present in the cell walls and intracellular tissues of fruits and vegetables [56]. While pectin is abundant in fruits, it is also found in vegetables, legumes, and nuts. For isolated and purified pectin, the molecular weight is determined by the extraction modes and conditions used, and the average molecular weight is typically between 10 and 100 kDa. Pectin meets the definition of dietary fiber for nutrition labeling based on its effect of attenuating blood cholesterol levels [39].

Starch resistant to amylase hydrolysis is termed resistant starch (RS) [72]. RS is classified into five types based on its structure and formation: Type 1 starch granules are embedded in indigestible plant material is physically trapped within indigestible matrices; Type 2 maintains its natural crystalline structure; Type 3 crystallized starch forms during heating and cooling cycles; Type 4 results from chemical modification such as phosphorylation, esterification, cross-linking, or transglycosylation; and Type 5 develops when starch binds with lipids during cooking [72]. Type 2 RS is found in raw green bananas, raw potatoes, uncooked high-amylose maize/corn, and potato starch [72]. This type consists of amorphous layers preferentially degraded by α-amylase and a crystalline skeleton resistant to hydrolysis. Type 2 RS has been shown to help reduce insulin levels following a meal containing carbohydrates that raise blood glucose levels, qualifying it as a dietary fiber for nutritional labelling [39]. The FDA has determined that the scientific evidence suggests that cross-linked phosphorylated RS4 can help reduce insulin levels following a meal containing a carbohydrate that raises blood glucose levels [73].

Benefits of Dietary Fiber

Native (Physical) Benefits of Dietary Fiber in the GI Tract

The effects of fiber in the upper GI tract can depend on its physicochemical characteristics, including solubility and viscosity. When distributed in food chyme, dietary fiber changes its physical attributes and the interactions of food components and nutrients with the digestive tract wall. Soluble fiber can help increase food chyme viscosity and lower blood cholesterol, sugar absorption, and blood levels. Dietary fiber helps increase stool bulk and water content and decrease transit time, which could help reduce interaction between carcinogens and the gut wall, reducing bowel cancer risk [74]. A high-fiber diet can also help promote satiation, increase satiety, and reduce energy intake.

Dietary Fiber Fermentation and Benefits

Dietary fiber, resisting breakdown in the upper digestive tract, enters the large intestine, where soluble fibers are fermented by fiber-degrading bacteria, providing an essential energy and carbon source for the intestinal microbiota [49]. The effects of microbial fiber fermentation and metabolism extend beyond the GI tract, influencing various body systems through the gut-brain, gut-liver, gut-kidney, and gut-heart axes [75-77].

The large intestine hosts around 1,000 bacterial species, with microbial populations reaching approximately 10^{11}-10^{12} CFU/g of colon content [78,79]. The colonic environment, with its slow transit time (2-60 hours) and favorable pH (6-8), is ideal for bacterial growth [80]. Intestinal epithelial cells (IECs) protect underlying body tissues from commensal microbes and invading pathogens by secreting a mucus layer of glycoprotein with 80% carbohydrate content [81]. This mucus acts as a physical barrier and a habitat for beneficial bacteria, providing binding sites and energy sources for microbes. Dietary fiber is crucial for maintaining this mucus barrier homeostasis and enhancing immune tolerance in the gut. When fiber intake is insufficient, the gut microbiota may degrade the colonic mucus barrier more rapidly than it can be regenerated, increasing the risk of pathogen invasion [82].

Gut microbes possess a diversity of carbohydrate-degrading enzymes, with over 130 Glycoside Hydrolase (GH) families, 22 Polysaccharide Lyase (PL) families, and 16 carbohydrate esterase families, allowing them to degrade various fiber sources and switch among different available fiber sources [43]. These microbes can work synergically to break down complex dietary fibers. PL-producing bacteria act as primary degraders that break down long-chain carbohydrates into oligosaccharides, which secondary degraders then ferment [72]. Gut microbes can quickly utilize these generated monosaccharides via glycolytic pathways for pyruvate production and subsequent ATP generation [83]. Cross-feeders, while not necessarily degrading carbohydrates themselves, use the by-products produced by the primary and secondary degraders, further facilitating the breakdown of complex fibers [72]. Around 30 to 50 g of bacterial biomass is produced for every 100 g of carbohydrate fermented, contributing to increased fecal mass [84].

Once pyruvate is produced primarily from carbohydrates and other substrates, the human gut microbiota employs various fermentation strategies to generate energy. The fermentation process produces a variety of metabolites, including gases; such as hydrogen, methane, carbon dioxide; and SCFAs like acetate, propionate, and butyrate, and other metabolites such as formate, succinate, lactate, and alcohols like ethanol and propanol [23]. While fermentation is essential for healthy gut function, low molecular weight fibers can ferment quickly in the proximal colon, produce excessive gas, and cause bloating and discomfort. This fermentation process contributes to the most common side effects of fiber consumption,

such as diarrhea and bloating [50]. In contrast, slow-fermenting fibers are more beneficial, distributing SCFA production along the entire colon and enhancing their health effects. The molecular structure of fibers, such as their molecular weight, chain length, and glycosidic bonds, affects the fermentation rate.

SCFAs are key to colonic health, supporting cellular integrity and metabolism while regulating pH and inhibiting pathogen growth. SCFAs account for up to 60% of dietary fiber fermentation end products, and 95% are absorbed by colonocytes [84]. Once absorbed into the bloodstream, SCFAs serve as an energy source for peripheral tissues, with acetate metabolized systemically in the organs, while propionate is processed mainly in the liver. It is estimated that SCFAs contribute about 10% of daily energy requirements [85]. SCFAs also possess anti-inflammatory properties, stimulating IECs and immune cells to produce anti-inflammatory cytokines and regulate immune responses. Excess SCFAs are transported to the liver for incorporation into metabolic processes such as gluconeogenesis, lipogenesis, and cholesterol synthesis [23]. Butyrate is the preferred energy source for colonic epithelial cells, promoting their proliferation, enhancing mucin production by goblet cells, and supporting tight junction integrity [86]. Different fibers produce varying amounts and ratios of SCFAs, and their production rate also varies. A diverse intake of dietary fibers supports a richly diverse and stable gut bacterial population, promoting the production of SCFAs and enhancing overall health [28]. SCFA production can help inhibit the growth of pathogenic organisms by lowering luminal and fecal pH, while a low pH environment can help promote beneficial bacteria. A reduced pH environment decreases the degradation of peptides and the formation of toxic compounds like ammonia, amines, and phenolic substances, while inhibiting harmful bacterial enzyme activity [21].

In addition to SCFA generation, pyruvate fermentation produces small amounts of alcohol, including ethanol, propanol, and butanediol, which may contribute to non-alcoholic fatty liver disease in elevated amounts [87,88]. The fermentation and subsequent absorption of SCFAs and alcohols highlight the complex metabolic interactions between gut microbiota and host health.

Dietary Fiber Reduces Blood Cholesterol and Cardiovascular Disease Risk

Cholesterol has vital biological functions, including stabilizing cell membranes and serving as a precursor for steroid hormones, bile acids, and vitamin D. However, cholesterol accumulation in the bloodstream (hypercholesterolemia) can cause atherosclerotic plaques within artery walls, leading to heart attacks and strokes. High levels of fasting total cholesterol, high-density lipoprotein (HDL), and LDL are well-known risk factors for CVD [89]. Cholesterol absorption in the small intestine is vital to human

health and clinical studies have linked cholesterol absorption with plasma concentration of total and LDL cholesterol [90]. Many epidemiologic and clinical studies, summarized in Table 2, suggest that adequate fiber intake consistently lowers blood cholesterol and LDL cholesterol levels, which help reduce the risk of CVD.

Study	Study Population	Design	Duration	Intervention	Treatment Results
Ribas (Ribas et al. 2015) [91]	N=51 (control=25, psyllium=26) Mild to moderate hypercholesterolemia 6-19 years	Randomized, double-blind, double-blind placebo-controlled	8 weeks	7 g psyllium	Total cholesterol: -0.39 mmol/L, (-7.7%) LDL cholesterol: -0.39 mmol/L, (10.7%)
Knopp (Knopp et al. 1999) [92]	Fiber supplement (n=52) or placebo (n=50) Mild to moderate hypercholesterolemia (LDL cholesterol: 3.37-4.92 mmol/L)	Randomized, Placebo-controlled	15 weeks	20 g guar gum and pectin	Total cholesterol, -0.53 mmol/L, (-8.5%) LDL cholesterol: -0.51 mmol/L, (-12.1%)
Wolever (Wolever et al. 2021) [93]	oat β-glucan (n=96) or control (n=95) LDL cholesterol: 3-5 mmol/L	Randomized parallel	4 weeks	Oat β-glucan 3 g	Total cholesterol, -0.226 mmol/L LDL cholesterol -0.21 mmol/L
Davidson (Davidson et al. 1991) [94]	N=156 (6 fiber groups; n=20-23 each; and control n=15) LDL cholesterol 3.37 -4.14 mmol/L 18-65 years	Randomized control	6 weeks	β-glucan rich meals, 84 g oatmeal; 56 g oat bran; 84 g oat bran	LDL cholesterol: -10.1%, -15.9%, -11.5%
Jenkins (Jenkins DJ et al. 2002) [95]	N=68 LDL cholesterol: >4.1 mmol/L 33-82 years	Randomized crossover	4 weeks	3 g β-glucan or 7 g psyllium	Total cholesterol: -2.1% LDL cholesterol: -1.7 % CVD risk: -4.2%
Ho (Ho et al. 2017) [96]	N=370 (12 studies) 25.7 years	Meta-analysis	>3 weeks	3 g Konjac glucomannan	LDL cholesterol: -0.35 mmol/L (-10%)
Tuomilehto (Tuomilehto et al. 1988) [97]	N=23 Hypercholesterolemic (8.0 and 14.3 mmol/l)	Single arm	50 weeks	15-30 g guar gum	Total cholesterol: -1.0 mmol/L LDL cholesterol: -15%

Study	Study Population	Design	Duration	Intervention	Treatment Results
Jensen(Jensen et al. 1993) [98]	N=29 (n=15 fiber, n=14 control) Hypercholesterolemic (LDL cholesterol: 167±14 mg/dL) 39-69 years	Randomized control	4 weeks	5 g mixture of psyllium pectin guar gum locust bean gum	Total cholesterol: -25 mg/dL, (-10%) LDL cholesterol: -23 mg/dL, (-14%)
Haskell (Haskell et al. 1992) [99]	4 studies (n=58, n=42, n=28, n=46) Total cholesterol: >5.17 mmol/L 20-75 years	Meta-analysis	4-12 weeks	15 g psyllium husk, pectin, guar and locust bean gums 10 g guar gum	Total cholesterol: – 8.3% LDL cholesterol: -12.4%
Brown (Brown et al. 1999) [15]	(N=2,990) 67 studies 50 years	Meta-analysis		2-10 g/day of soluble fiber	Total cholesterol: −1.73 mg/dL LDL cholesterol: −2.21 mg/dL
Abbreviations: LDL: Low-Density Lipoprotein					

Table 2: Perspective, clinical studies, and meta-analyses assessing cholesterol reduction effects of dietary fiber or by year.

In a prospective cohort study of 2,532 men and 3,429 women, the relationship between dietary fiber intake and cardiovascular disease risk factors was examined [100]. In the study, total dietary and non-soluble fiber intakes were inversely associated with hypercholesterolemia. An inverse association was observed of total dietary fiber, soluble fiber, and insoluble fiber intakes with elevated apolipoprotein B, a key component of LDL concentrations, and elevated apolipoprotein B to apolipoprotein A (HDL key component) ratios, a relevant marker of cardiovascular disease risk. In a prospective randomized atherosclerosis prevention trial with 543 children between the ages of 8 months and 9 years, nutrient fiber intakes, weight, height, and serum total, HDL, and LDL cholesterol and triglyceride concentrations were analysed [101]. It was observed that serum cholesterol values correlated inversely with fiber intake; serum cholesterol concentrations decreased with increasing fiber intake.

Cholesterol is used in the liver synthesis of bile acids, which, when secreted in the duodenum, forms an oil fatty emulsion in the digestion tract, aiding further enzymatic fat digestion. Bile acids can be absorbed in the small intestine and recycled through the liver [102]. SDF can increase the viscosity of the food chyme, bind bile acid, reduce its reabsorption in the small intestine, and help the body excrete the bile acids into the large intestine, thus reducing bile acid recycling. Because of this reduced amount of recycled bile acids, the liver will utilize more cholesterol from the blood to make new bile acids, thereby lowering blood cholesterol [102]. Soluble fiber from oats, plant gums, and psyllium has been shown to reduce total and LDL cholesterol without affecting HDL concentrations [15,47,103,104].

Fiber viscosity, rather than the quantity consumed, is essential in reducing total cholesterol and LDL cholesterol [105]. Researchers conducted a three-arm experiment to compare the lipid-lowering effects of different dietary fibers: wheat bran with low-viscosity, psyllium with medium-viscosity, and a high-viscosity fiber blend [105]. Reduction in LDL cholesterol was greater with the high-viscosity fiber blend compared with the medium-viscosity psyllium and low-viscosity wheat bran, despite participants consuming a lower quantity of the high-viscosity fiber blend [105]. Confirming these findings, other low-viscosity fibers (acacia gum or fruit juice) did not change plasma lipids or lipoprotein cholesterol concentrations [98,106,107]. A randomized, single-blind study of 57 healthy participants found that consuming 30 g daily of RS (from either raw or retrograded high-amylose cornstarch) for three weeks did not significantly affect serum cholesterol or triacylglycerol levels compared with a glucose supplement [108].

Dietary Fiber Reduces Insulin Resistance and Glycemic Blood Sugar

Blood glucose, and insulin levels and sensitivity are associated with diabetes and numerous diseases such as nerve damage,

kidney disease, eye problems, and cardiovascular issues [109.110]. Research has demonstrated that consuming foods with a high-glycemic index is correlated with increased mortality and cardiovascular disease risk compared with diets with a lower glycemic index [110]. High-glycemic index foods interact with insulin resistance in individuals with higher BMI to amplify postprandial blood sugar responses, potentially exacerbating adverse health outcomes through this synergistic effect [110]. Insulin resistance can also alter systemic lipid metabolism, which then leads to the development of dyslipidemia due to high levels of plasma triglycerides, low levels of HDL, and high levels of LDL, leading to plaque formation [111].

Large cohort studies have found that high-fiber whole grains (brown rice, rye, oats, wheat bran) are strongly associated with lower diabetes risk [19,112]. However, fiber from fruits and vegetables does not appear to have as strong an association [19]. Several studies supported the finding that a high-fiber diet helps control blood glucose and insulin resistance, which is vital because these are risk factors for diabetes and cardiovascular disease, see Table 3.

Study	Baseline Demographics	Design	Duration	Intervention	Treatment Results
Lu (Lu et al. 2004) [113]	N=15, people with diabetes 60±2 years Fasting glucose: 7.3-7.6 mmol/L Fasting serum insulin: 90-100 pmol/L	Randomized control	5 weeks	15 g arabinoxylan	Fasting glucose: -10% Fasting insulin: -21%
Khoury (El Khoury et al. 2014) [114]	N= 24, healthy volunteers 20-30 years Fasting blood glucose: <7 mmol/L	Randomized crossover	Acute (260 minutes)	4 or 8 g alginate	Glucose increment: -30-40% Insulin peak: -46%
Hartvigsen (Hartvigsen et al. 2014) [115]	N=15, people with metabolic syndrome 52-72 years Fasting blood glucose: 5.9±0.4 mmol/L	Randomized Crossover	1 week	4.2 g β-glucan	Postprandial glucose: -15%
Abutair (Abutair et al. 2016) [116]	N=40 (n=20 per group), people with diabetes 35-60 years Fasting blood glucose: 163 mg/dL Insulin: 27.9 uIU/mL	Randomized control	8 weeks	10.5 g psyllium	Fasting blood glucose: -44 mg/dl Insulin level: -8.2 μIU/mL
Ziai (Ziai et al. 2005) [117]	N=36, people with diabetes (n=21 psyllium vs n=15 placebo) 35-70 years Fasting blood glucose: 200 (mg/dL) Insulin: 8 (uU/mL)	Randomized control	8 weeks	10 g psyllium	Fasting glucose: -60 mg/dL Insulin: -1.7 μIU/mL
Williams (Williams JA et al. 2004) [118]	N=48, healthy volunteers 19-75 years Fasting blood glucose: 2.7-5.9 mmol/L	Randomized control crossover	Acute (180 minutes)	1.6 g alginate and 5.5 g guar gum	Postprandial glucose: -30%

Study	Baseline Demographics	Design	Duration	Intervention	Treatment Results
Larson (Larson et al. 2021) [119]	N=48, healthy volunteers 18-65 years Fasting blood glucose: <110 mg/dL	Randomized control	Acute (240 minutes)	40 g acacia gum	Postprandial glucose: -10%
Stewart (Stewart et al. 2018) [120]	N=35, healthy volunteers 18-74 years Fasting blood glucose: 5±0.1 mmol	Randomized control	Acute (180 minutes)	17 g RS4	Postprandial glucose: -40% Insulin: -35%
Arias-Córdona (Arias-Córdova et al. 2021) [121]	N=17, people with diabetes 28-65 years Fasting blood glucose: 203±77 mg/dL Insulin: 7.4±4.7 uU/mL	Randomized Control Crossover	6 weeks	40 g RS2 with controlled digestible starch	No significant effects
Abbreviations: RS, Resistant Starch					

Table 3: Perspectives, clinical studies, and meta-analysis assessing blood glucose reduction and insulin resistance reduction effects of dietary fiber.

The mechanisms by which dietary fiber reduces blood sugar levels have been widely studied [22,122,123]. One possible mechanism is that soluble fiber attracts water in the gut, forming a gel, which can slow digestion [122]. This may help prevent blood glucose surges after eating. The increased viscosity of digestive contents can slow simple sugar absorption into the bloodstream, and this process improves insulin sensitivity and thus helps maintain blood sugar levels [21,22,124]. In a human study, guar gum was found to delay gastric emptying and reduce both plasma glucose and insulin responses to an oral glucose load [122]. These results indicate that guar gum improves glucose tolerance predominantly by reducing glucose absorption in the small intestine. The viscosity and glucose reduction effects diminished when the dietary fiber molecular weight was reduced [125,126].

Multiple mechanisms could explain the beneficial effects of RS, though these remain incompletely verified [127,128]. RS regulates hypoglycemic-related enzymes by diluting the total carbohydrate content with indigestible starch. RS type 2 or 3 attenuates postprandial glucose response and other mechanisms relating to intestinal microbiota disorder [127]. Research suggests that RS may reduce energy intake at a subsequent meal but does not significantly impact overall 24-hour food intake or feelings of satiety in overweight individuals [129]. Additionally, SCFAs, such as acetic, propionic, and butyric acid, are produced through the fermentation of RS and improve insulin resistance and T2D by regulating metabolic pathways at cellular, tissue, and organ levels [127].

Dietary Fiber Induces Satiation and Reduces Body Weight

Dietary fiber promotes satiety for prolonged periods, thereby helping regulate overall caloric intake and reduce obesity risk [130]. Multiple mechanisms describe the influence of fiber on satiation and satiety, including increased chewing, increased feelings of fullness, and slowed gastric emptying [130]. High-fiber foods may increase satiety through the increase in time spent chewing [130]. Increased chewing promotes saliva and gastric acid production, which may increase gastric distention [130]. Viscous soluble fiber absorbs water, which may also increase stomach distention that promotes a feeling of satiety [130]. Viscous chyme can slow gastric emptying [131]. Reduced and steady postprandial glucose and insulin responses are sometimes correlated with satiation and satiety [130]. As food moves through the upper and lower GI tract, various satiety-related hormones are released, and signals are sent to the brain [132]. Many of these signals are gut hormones, including ghrelin, polypeptide YY (pYY), and glucagon-like peptide, and are thought to regulate satiety, food intake, and overall energy balance [132].

Many epidemiologic and cross-sectional studies have indicated that diets low in dietary fiber are associated with an increased risk for obesity [133]. Prospective cohort studies report that people consuming higher amounts of fiber weigh less than those consuming lesser amounts [1,134,135]. Clinical studies indicate that higher fiber intake is linked to increased satiety and reduced energy intake, resulting in lower body weight, see Table 4. Diets high in fiber are also typically lower in fat and energy density,

which helps maintain a healthy body weight [132]. An analysis of more than 50 intervention studies assessing the relationship between energy intake, body weight, and fiber intake revealed that increasing fiber intake by 14 g/day was associated with a 10% decrease in energy intake and a 2 kg weight loss over about 4 months [132]. A systematic review of 44 studies involving 107 treatments examining the effect of fiber on appetite and energy intake showed that only 39% of treatments significantly reduced subjective appetite, and 22% reduced food or energy intake [136]. Certain fibers, like β-glucan and rye bran, consistently enhanced satiety across multiple studies, although most fibers did not show significant effects in acute studies [136].

Study	Study Population	Design	Duration	Intervention	Treatment Results
Guerin-Deremaux (Guerin-Deremaux et al. 2011) [137]	N=100, overweight 35-55 years BMI: 24-28 kg/m^2	Randomized control	9 weeks	24 g polydextrose	Increased satiety 1 kg weight loss
Rigaud (Rigaud et al. 1998) [21]	N=14, healthy volunteers 18-50 years BMI: 19-25 kg/m^2	Randomized crossover control	Acute (6 hours)	7.4 psyllium	Hunger feelings, -13% Energy intake -17%
Larson (Larson et al. 2021) [119]	N=48, healthy volunteers 18-65 years BMI: 18-29 kg/m^2	Randomized crossover control	Acute (240 minutes)	40 g acacia gum	Satiety improvement
Akyol (Akyol et al. 2014) [138]	N=25, healthy volunteers 19-25 years BMI 18-29 kg/m^2	Randomized crossover control	Acute (240 minutes)	3 g β-glucan	No significant effect on satiety
Calame (Calame et al. 2011) [139]	N=58, healthy volunteers 20-60 years BMI: 19-27 kg/m^2	Randomized crossover control	Acute (180 minutes)	10-40 g gum arabic	Energy intake reduction Satiety increased
Kovacs (Kovacs et al. 2001) [140]	N=28, overweight 19-56 years BMI: 24-34 kg/m^2	Randomized crossover control	15 weeks	7.5 g guar gum	Energy intake reduction Satiety increase Weight loss

BMI: Body Mass Index

Table 4. Clinical studies assessing satiation satiety and energy intake effects of dietary fiber.

Studies have explored the effects of short-chain carbohydrates on GI function and satiety [141-144]. One study on Fructooligosaccharides (FOS) and partially hydrolyzed guar gum (PHGG) found that FOS increased gastric emptying, and both fibers reduced small intestinal transit time without altering hunger or satiety hormone levels [144].

Specific dietary fiber characteristics, such as molecular weight, viscosity, gel-forming capacity, and fermentability, were analyzed for their impact on appetite-related outcomes in healthy individuals [145]. While gel-forming fibers showed consistent efficacy, other characteristics like viscosity and fermentability did not correlate with effectiveness [145]. A MRI study researched the physiological and appetitive responses to alginate gelling feeds in healthy men [146]. MRI measurements established small bowel water content, gastric content volume, and superior mesenteric artery blood flux; results demonstrated modified GI responses and increased small bowel water content, though subjective appetite scores were unaffected [146]. Although some evidence supports the effects of dietary fiber on promoting and enhancing satiety, the variations in dietary fiber measurement and study designs contribute to inconsistent results, making it challenging to draw generalized conclusions about the specific properties of dietary fiber's effects on appetite. Improved standards for characterizing and reporting dietary fiber sources are needed to enhance the reliability of future research on dietary fiber and human physiology.

Dietary Fiber Promotes Laxative Effects

Constipation is typically defined as having three or fewer bowel movements per week, having trouble or pain during bowel movements, or passing small, hard, "pebbly" stools [28]. It can also be accompanied by symptoms such as bloating, cramping, and nausea. Chronic constipation increases the risk of developing conditions like diverticular disease and hemorrhoids. Dietary fiber plays a crucial role in alleviating constipation [27]. High molecular

weight SDF binds water, forming a gel that softens and bulks stool [27]. Insoluble dietary fiber can mildly irritate the intestinal lining, stimulating the secretion of water and mucus, which promotes stool movement [27]. Additionally, low molecular weight dietary fibers can be fermented by gut bacteria, which increases the water and mass content of stools, making them softer and easier to pass [28].

Fiber's water retention ability is essential for stool hydration and creating a laxative effect [147]. The physical consistency of stool is closely tied to its water content, with normal stools containing about 74% water, hard stools less than 72%, and soft stools at least 76% [27]. Soft stools are quickly propelled by low amplitude, frequent, and rapid peristaltic waves in the colon, making them easy to evacuate and increasing daily bowel movements [27]. In contrast, hard stools require high-amplitude waves for propulsion, which can cause discomfort and difficulty during passage [27]. MRI was used to assess the laxative effects of psyllium and was shown to increase colonic volume and water content in the bowel while decreasing bowel transit [148].

Short-chain carbohydrates, such as Fructooligosaccharides (FOS) and Galactooligosaccharides (GOS), that are readily fermented by gut microbiota, produce gases like hydrogen, carbon dioxide, and methane [149]. This fermentation process contributes to the common side effects of fiber consumption, such as diarrhea and bloating [50]. In the colon, fiber fermentation by microbiota results in gases and SCFAs like butyrate, acetate, and propionate, which create an osmotic load, accelerating intestinal transit [50]. Butyrate, an important energy source for the colonic mucosa, also stimulates neurons in the myenteric plexus, enhancing gut motility [150].

Inulin can increase stool frequency and soften stools, suggesting that chicory inulin could potentially serve as a dietary intervention for managing constipation [151]. Daily inulin supplementation improved bowel function and quality of life in constipated elderly individuals [151]. Study participants reported improved digestive satisfaction and reduced defecation difficulties, though some experienced mild GI symptoms [151]. Other low molecular weight dietary fibers, such as PHGG, have also demonstrated reduced laxative use among long-term care facility residents compared with a placebo when given as a dietary supplement [152].

Due to the differing actions of various fiber types on constipation, it is recommended to include a wide range of high-fiber foods in the diet, such as whole grains, fruits, legumes, and vegetables [28]. Gradually increasing fiber intake is advised, as a sudden significant increase can lead to bloating and cramping [28]. Additionally, drinking more fluids while increasing fiber intake can help mitigate these side effects [28].

Dietary Fiber Regulation and Health Claims

Authorities in different countries and markets may use their own evaluation systems to assess the health benefits and claims associated with dietary fiber, relying on scientific substantiation. Despite some regional variations, there is more similarity than difference in how dietary fiber is defined across various markets.

In the United States, several health claims related to dietary fiber are recognized [39]. The FDA approves the health benefits of general dietary fiber consumption [39]. Consuming a diet low in fat and high in grain products, fruits, and vegetables that contain dietary fiber may reduce the risk of certain cancers [18]. Additionally, diets low in saturated fat and cholesterol and rich in fruits, vegetables, and grain products that contain specific types of dietary fiber, particularly soluble fiber, may help lower the risk of heart disease [153]. Further health benefits are FDA approved for specific dietary fibers as described previously. For example, consuming 3 g of β-glucan from oats, barley, or 7 g of arabinoxylan from psyllium husk is accepted for lowering blood lipids and reducing the risk of CVD, as per the code of federal regulations, 21 CFR 101.81 [154]. The FDA has approved soluble fibers like konjac gum (glucomannan), locust bean gum (galactomannan), pectin (galacturonan), and hydroxypropyl methylcellulose (HPMC) for their benefits in reducing blood cholesterol levels [39,153]. Additionally, acacia gum (arabinogalactan), guar gum (galactomannan), arabinoxylan, alginate (mannuronan co-glucuronan), and RS (α-glucan) are recognized for their ability to lower blood glucose levels. Inulin (fructan, FOS), Galactooligosaccharides (GOS), and RS improve calcium absorption, while RS and polydextrose can help reduce energy intake during meals. Furthermore, insoluble cellulose (β-glucan) fiber is approved for its laxative effects [39].

The EFSA highlighted that the physical-chemical properties of dietary fiber lead to different physiological effects, but a specific property, such as solubility, does not predict these effects [155]. While established analytical methods can measure total dietary fiber content and types, the physiological effects of dietary fiber in humans vary based on the fiber's unique characteristics, dose, and mode of administration [155]. The EFSA Panel concluded that dietary fiber is not sufficiently characterized to establish a cause-and-effect relationship with the claimed health effects [155]. EFSA approves health benefits and claims on a case-by-case basis, and there needs to be an established cause-and-effect relationship between the food and the effect [32]. Dietary fiber that is approved for reducing postprandial glycemic response includes 8 g of arabinoxylan per 100 g of available carbohydrates in a meal, 4 g of β-glucans per 30 g of available carbohydrates in a meal, and 10 g of pectin in a meal [32]. For reducing or maintaining normal blood cholesterol levels, the approved dietary fibers are 3 g/day of β-glucan, 3 g/day of chitosan, 4 g/day of glucomannan,

10 g/day of guar gum, 6 g/day of pectin, and RS replacing 14% of total starch consumed [32]. For weight loss in an energy-restricted diet, 3 g/day glucomannan consumption is approved [32]. Daily consumption of over 10 g of wheat bran, containing cellulose and xylans, can help reduce intestinal transit time [32].

The Scientific Advisory Committee on Nutrition (SACN) of the United Kingdom recommends 30 g/day dietary fiber intake on average for the population [156]. SACN concludes that there is strong evidence from prospective cohort studies that increased intakes of total dietary fiber, particularly cereal fiber, are associated with a lower risk of cardio-metabolic disease and colorectal cancer [156]. Total dietary fiber, wheat fiber, and other cereal fiber increase fecal mass and decrease intestinal transit times [156]. High intake of oat bran and isolated β-glucans leads to lower total cholesterol, LDL cholesterol, triacylglycerol concentrations, and blood pressure [156].

In China, dietary fiber is defined in alignment with WHO standards [157]. A novel dietary fiber should provide at least one of the following health benefits: increasing stool bulk, promoting bowel movements or improving bowel regularity; lowering total cholesterol and LDL cholesterol levels; reducing fasting and postprandial blood glucose and insulin levels or enhancing insulin sensitivity; or providing fermentable substrates for colonic fermentation and increasing the number or activity of beneficial bacteria. Isolated dietary fibers recommended include GOS, FOS, inulin, polydextrose, β-glucan, cellulose, RS, alginate, guar gum, and pectin [158]. The Chinese Nutrition Society recommends an adequate intake of dietary fiber of 25 to 30 g/d [159].

In India, the recommended dietary fiber intake is 25 g/day for women and 38 g/day for men [160]. Dietary fiber is recognized as having a crucial role in delaying intestinal transit of consumed food, which supports proper bowel function and helps reduce the risk of chronic constipation, diverticular disease, and hemorrhoids. Additionally, dietary fiber is recognized to lower plasma cholesterol levels, CVD, diabetes, and obesity.

Conclusion

Dietary fibers vary in their sources, physiochemical properties, and health effects, influencing factors like blood cholesterol, blood glucose, cardiovascular health, weight management, and digestive functions. While intact fiber from fruits and vegetables provides general health benefits, not all isolated fibers are equally beneficial. Key characteristics such as solubility, fermentability, and viscosity determine their effects. Subsequent dietary fiber fermentation in the colon offers additional benefits. The gut microbiota mediates many benefits of dietary fiber, including appetite regulation and metabolic health. Despite extensive evidence of dietary fiber's benefits, the global fiber intake is less than recommended, and increasing fiber consumption is crucial for health promotion and disease prevention.

The rise of ultra-processed foods has led to a decline in dietary fiber intake, moving us away from more natural eating patterns [161]. Adopting a diet high in dietary fiber and reducing processed foods can help increase fiber intake and associated benefits. Despite advancements in modern diets, the issue of low dietary fiber intake remains a significant health concern [162]. Consumers need to make choices to consume more fiber, and food and supplement producers can assist in making higher fiber choices readily available. High dietary fiber is crucial for long-term health and could drive improvements in food industry practices. We can benefit our health by choosing high-fiber options and encouraging better nutritional standards in processed foods.

References

1. Reynolds A, Mann J, Cummings J, Winter N, Mete E, et al. (2019) Carbohydrate quality and human health: a series of systematic reviews and meta-analyses. Lancet 393: 434-445.

2. Barber TM, Kabisch S, Pfeiffer AFH, Weickert MO (2020) The Health Benefits of Dietary Fibre. Nutrients 12: 3209.

3. Hojsak I, Benninga MA, Hauser B, Kansu A, Kelly VB, et al. (2022) Benefits of dietary fibre for children in health and disease. Arch Dis Child 107: 973-979.

4. Bulsiewicz WJ (2023) The Importance of Dietary Fiber for Metabolic Health. Am J Lifestyle Med 17: 639-648.

5. Perez-Jimenez J (2024) Dietary fiber: Still alive. Food Chem 439: 138076.

6. Swinburn BA, Sacks G, Hall KD, McPherson K, Finegood DT, et al. (2011) The global obesity pandemic: shaped by global drivers and local environments. Lancet 378: 804-814.

7. O'Keefe SJ (2019) The association between dietary fibre deficiency and high-income lifestyle-associated diseases: Burkitt's hypothesis revisited. Lancet Gastroenterol Hepatol 4: 984-996.

8. Dayib M, Larson J, Slavin J (2020) Dietary fibers reduce obesity-related disorders: mechanisms of action. Curr Opin Clin Nutr Metab Care 23: 445-450.

9. Popkin BM, Ng SW (2022) The nutrition transition to a stage of high obesity and noncommunicable disease prevalence dominated by ultra-processed foods is not inevitable. Obes Rev 23: e13366.

10. Okunogbe A, Nugent R, Spencer G, Powis J, Ralston J, Wilding J (2022) Economic impacts of overweight and obesity: current and future estimates for 161 countries. BMJ Glob Health 7: e009773.

11. World Health Organization. (2024) Obesity and overweight.

12. Partula V, Deschasaux M, Druesne-Pecollo N, Latino-Martel P, Desmetz E, et al. (2020) Associations between consumption of dietary fibers and the risk of cardiovascular diseases, cancers, type 2 diabetes, and mortality in the prospective NutriNet-Sante cohort. Am J Clin Nutr 112: 195-207.

13. GBD 2017 Diet Collaborators. (2019) Health effects of dietary risks in 195 countries, 1990-2017: a systematic analysis for the Global Burden of Disease Study 2017. Lancet 393: 1958-1972.

14. Strasser B, Wolters M, Weyh C, Kruger K, Ticinesi A (2021) The Effects of Lifestyle and Diet on Gut Microbiota Composition, Inflammation and Muscle Performance in Our Aging Society. Nutrients 13: 2045.

15. Brown L, Rosner B, Willett WW, Sacks FM (1999) Cholesterol-lowering effects of dietary fiber: a meta-analysis. Am J Clin Nutr 69: 30-42.

16. McKeown NM, Meigs JB, Liu S, Saltzman E, Wilson PW, et al. (2004) Carbohydrate nutrition, insulin resistance, and the prevalence of the metabolic syndrome in the Framingham Offspring Cohort. Diabetes Care 27: 538-546.

17. Pereira MA, O'Reilly E, Augustsson K, Fraser GE, Goldbourt U, et al. (2004) Dietary fiber and risk of coronary heart disease: a pooled analysis of cohort studies. Arch Intern Med 164: 370-376.

18. U.S. Food and Drug Administration. 2016a. 21 CFR 101.76 Health Claims: Fiber-containing Grain Pproducts, Fruits, and Vegetables and Cancer.

19. Kyro C, Tjonneland A, Overvad K, Olsen A, Landberg R (2018) Higher Whole-Grain Intake Is Associated with Lower Risk of Type 2 Diabetes among Middle-Aged Men and Women: The Danish Diet, Cancer, and Health Cohort. J Nutr 148: 1434-1444.

20. Hu J, Wang J, Li Y, Xue K, Kan J (2023) Use of Dietary Fibers in Reducing the Risk of Several Cancer Types: An Umbrella Review. Nutrients 15: 2545.

21. Rigaud D, Paycha F, Meulemans A, Merrouche M, Mignon M (1998) Effect of psyllium on gastric emptying, hunger feeling and food intake in normal volunteers: a double blind study. Eur J Clin Nutr 52: 239-245.

22. Xie Y, Gou L, Peng M, Zheng J, Chen L (2021) Effects of soluble fiber supplementation on glycemic control in adults with type 2 diabetes mellitus: A systematic review and meta-analysis of randomized controlled trials. Clin Nutr 40: 1800-1810.

23. Oliphant K, Allen-Vercoe E (2019) Macronutrient metabolism by the human gut microbiome: major fermentation by-products and their impact on host health. Microbiome 7: 91.

24. Thomson C, Garcia AL, Edwards CA (2021) Interactions between dietary fibre and the gut microbiota. Proc Nutr Soc 23: 1-11.

25. Carlsen H, Pajari AM (2023) Dietary fiber - a scoping review for Nordic Nutrition Recommendations 2023. Food Nutr Res 67.

26. Hills RD Jr, Pontefract BA, Mishcon HR, Black CA, Sutton SC, et al. (2019) Gut Microbiome: Profound Implications for Diet and Disease. Nutrients 11: 1613.

27. McRorie JW Jr, McKeown NM (2017) Understanding the Physics of Functional Fibers in the Gastrointestinal Tract: An Evidence-Based Approach to Resolving Enduring Misconceptions about Insoluble and Soluble Fiber. J Acad Nutr Diet 117: 251-264.

28. Bellini M, Tonarelli S, Barracca F, Rettura F, Pancetti A, et al. (2021) Chronic Constipation: Is a Nutritional Approach Reasonable? Nutrients 13: 3386.

29. EFSA Panel on Dietetic Products N, Allergies. 2010a. Scientific Opinion on Dietary Reference Values for carbohydrates and dietary fibre. EFSA Journal 8: 1462.

30. World Health Organization. (2023) Carbohydrate intake for adults and children: WHO guideline.

31. U.S. Department of Agriculture, U.S. Department of Health and Human Services. 2020. Dietary Guidelines for Americans, 2020-2025. 9th ed.

32. Stephen AM, Champ MM, Cloran SJ, Fleith M, van Lieshout L, et al. (2017) Dietary fibre in Europe: current state of knowledge on definitions, sources, recommendations, intakes and relationships to health. Nutr Res Rev 30: 149-190.

33. Lin B-HL, Guthrie J, Smith T (2023) Dietary Quality by Food Source and Demographics in the United States, 1977-2018.

34. Thompson HJ, Brick MA (2016) Perspective: Closing the Dietary Fiber Gap: An Ancient Solution for a 21st Century Problem. Adv Nutr 7: 623-626.

35. Ioniță-Mîndrican CB, Ziani K, Mititelu M, Oprea E, Neacșu SM, et al. (2022) Therapeutic Benefits and Dietary Restrictions of Fiber Intake: A State of the Art Review. Nutrients 14: 2641.

36. Food and Agriculture Organization of the United Nations, World Health Organization. (2021) Guidelines on Nutrition Labelling, CXG2-1985.

37. Howlett JF, Betteridge VA, Champ M, Craig SA, Meheust A, et al. (2010) The definition of dietary fiber - discussions at the Ninth Vahouny Fiber Symposium: building scientific agreement. Food Nutr Res 54.

38. U.S. Food and Drug Administration. 2016d. CFR 21.101.9 Food Labeling - Nutrition Labeling of Food.

39. U.S. Food and Drug Administration. (2018) Review of the Scientific Evidence on the Physiological Effects of Certain Non-Digestible Carbohydrates.

40. U.S. Food and Drug Administration. (2024) Question and Answers on Dietary Fiber

41. Khorasaniha R, Olof H, Voisin A, Armstrong K, Wine E, et al. (2023) Diversity of fibers in common foods: Key to advancing dietary research. Food Hydrocolloids 139: 108495.

42. Cantarel BL, Lombard V, Henrissat B (2012) Complex carbohydrate utilization by the healthy human microbiome. PLoS One 7: e28742.

43. Wardman JF, Bains RK, Rahfeld P, Withers SG (2022) Carbohydrate-active enzymes (CAZymes) in the gut microbiome. Nat Rev Microbiol 20: 542-556.

44. Devries J, Camire M, Cho S, Craig S, Gordon D, et al. (2001) The definition of dietary fiber. Cereal Foods World 46:112-129.

45. AOAC International. 2020. Official Methods of Analysis. 21 ed. Rockville, MD.

46. Guo MQ, Hu X, Wang C, Ai L (2017) Polysaccharides: Structure and Solubility. InTechOpen. (Solubility of Polysaccharides).

47. Tosh SM, Brummer Y, Miller SS, Regand A, et al. (2010) Processing affects the physicochemical properties of beta-glucan in oat bran cereal. J Agric Food Chem 58: 7723-7730.

48. Williams BA, Grant LJ, Gidley MJ, Mikkelsen D (2017) Gut Fermentation of Dietary Fibres: Physico-Chemistry of Plant Cell Walls and Implications for Health. Int J Mol Sci 18: 2203.

49. Guan ZW, Yu EZ, Feng Q (2021) Soluble Dietary Fiber, One of the Most Important Nutrients for the Gut Microbiota. Molecules 26: 6802.

50. Bellini M, Tonarelli S, Nagy AG, Pancetti A, Costa F, et al. (2020) Low FODMAP Diet: Evidence, Doubts, and Hopes. Nutrients 12: 148.

51. Sperber AD, Bangdiwala SI, Drossman DA, Ghoshal UC, Simren M, et al. (2021) Worldwide Prevalence and Burden of Functional Gastrointestinal Disorders, Results of Rome Foundation Global Study. Gastroenterology 160: 99-114.e113.

52. Enck P, Aziz Q, Barbara G, Farmer AD, Fukudo S, et al. (2016) Irritable bowel syndrome. Nat Rev Dis Primers 2: 16014.

53. Anbazhagan AN, Priyamvada S, Alrefai WA, Dudeja PK (2018) Pathophysiology of IBD associated diarrhea. Tissue Barriers 6: e1463897.

54. Varney J, Barrett J, Scarlata K, Catsos P, Gibson PR, et al. (2017) FODMAPs: food composition, defining cutoff values and international application. J Gastroenterol Hepatol 32: 53-61.

55. Draget KI, Moe ST, Skjak-Bræk G, Smidsrød O (2006) Alginates. In: Stephen AM, Phillips GO, Williams PA, editors. Food Polysaccharides and Their Applications. Boca Raton: Taylor & Francis.

56. Izydorczyk M, Cui SW, Wang Q (2005) Polysaccharide Gums: Structures, Functional Properties, and Applications. In: Cui SW, editor. Food Carbohydrates, Chemistry, Physical Properties, and Applications. Boca Raton: Taylor & Francis.

57. Bernstein AM, Titgemeier B, Kirkpatrick K, Golubic M, Roizen MF (2013) Major cereal grain fibers and psyllium in relation to cardiovascular health. Nutrients 5: 1471-1487.

58. Marlett JA, Fischer MH (2003) The active fraction of psyllium seed husk. Proc Nutr Soc 62: 207-209.

59. Singla A, Gupta OP, Sagwal V, Kumar A, Patwa N, et al. (2024) Beta-Glucan as a Soluble Dietary Fiber Source: Origins, Biosynthesis, Extraction, Purification, Structural Characteristics, Bioavailability, Biofunctional Attributes, Industrial Utilization, and Global Trade. Nutrients 16: 900.

60. Dhingra D, Michael M, Rajput H, Patil RT (2012) Dietary fibre in foods: a review. J Food Sci Technol 49: 255-266.

61. Ashaolu TJ, Ashaolu JO, Adeyeye SAO (2021) Fermentation of prebiotics by human colonic microbiota in vitro and short-chain fatty acids production: a critical review. J Appl Microbiol 130: 677-687.

62. Franco-Robles E, López MG (2015) Implication of fructans in health: immunomodulatory and antioxidant mechanisms. ScientificWorldJournal 2015: 289267.

63. Raninen K, Lappi J, Mykkanen H, Poutanen K (2011) Dietary fiber type reflects physiological functionality: comparison of grain fiber, inulin, and polydextrose. Nutr Rev 69: 9-21.

64. Niness KR (1999) Inulin and oligofructose: what are they? J Nutr 129: 1402S-1406S.

65. Schneeman BO (1999) Fiber, inulin and oligofructose: similarities and differences. J Nutr 129: 1424S-1427S.

66. Dionísio M, Grenha A (2012) Locust bean gum: Exploring its potential for biopharmaceutical applications. J Pharm Bioallied Sci 4: 175-185.

67. Behera SS, Ray RC (2016) Konjac glucomannan, a promising polysaccharide of Amorphophallus konjac K. Koch in health care. Int J Biol Macromol 92: 942-956.

68. Kapoor DU, Sharma H, Maheshwari R, Pareek A, Gaur M, et al. (2024) Konjac glucomannan: A comprehensive review of its extraction, health benefits, and pharmaceutical applications. Carbohydr Polym 339: 122266.

69. Ashour MA, Fatima W, Imran M, Ghoneim MM, Alshehri S, et al. (2022) A Review on the Main Phytoconstituents, Traditional Uses, Inventions, and Patent Literature of Gum Arabic Emphasizing Acacia seyal. Molecules 27: 1171.

70. Cox LM, Cho I, Young SA, Anderson WH, Waters BJ, et al. (2013) The nonfermentable dietary fiber hydroxypropyl methylcellulose modulates intestinal microbiota. Faseb j 27: 692-702.

71. Zhang L, Fu S (2020) Preparation of Hydroxypropyl Methylcellulose Acetate Succinate with a Narrow Molecular Weight Dispersion. Paper and Biomaterials 5: 36-43.

72. Dobranowski PA, Stintzi A (2021) Resistant starch, microbiome, and precision modulation. Gut Microbes 13: 1926842.

73. U.S. Food and Drug Administration. (2019) FDA Grants Citizen Petition on Cross-Linked Phosphorylated RS4 as a Dietary Fiber.

74. Celiberto F, Aloisio A, Girardi B, Pricci M, Iannone A, et al. (2023) Fibres and Colorectal Cancer: Clinical and Molecular Evidence. Int J Mol Sci 24: 13501.

75. Ahlawat S, Asha, Sharma KK (2021) Gut-organ axis: a microbial outreach and networking. Lett Appl Microbiol 72: 636-668.

76. Silvester JA (2021) Editorial: No organ is an island: the role of gut-organ axes in human health and disease. Curr Opin Gastroenterol 37: 545-546.

77. Saxami G, Kerezoudi EN, Eliopoulos C, Arapoglou D, Kyriacou A (2023) The Gut-Organ Axis within the Human Body: Gut Dysbiosis and the Role of Prebiotics. Life (Basel) 13: 2023.

78. Quigley EM (2013) Gut bacteria in health and disease. Gastroenterol Hepatol (N Y) 9: 560-569.

79. Abenavoli L, Scarpellini E, Colica C, Boccuto L, Salehi B, et al. (2019) Gut Microbiota and Obesity: A Role for Probiotics. Nutrients 11: 2690.

80. Sarosiek I, Selover KH, Katz LA, Semler JR, Wilding GE, et al. (2010) The assessment of regional gut transit times in healthy controls and patients with gastroparesis using wireless motility technology. Aliment Pharmacol Ther 31: 313-322.

81. Suriano F, Nystrom EEL, Sergi D, Gustafsson JK (2022) Diet, microbiota, and the mucus layer: The guardians of our health. Front Immunol 13:953196.

82. Desai MS, Seekatz AM, Koropatkin NM, Kamada N, Hickey CA, et al. (2016) A Dietary Fiber-Deprived Gut Microbiota Degrades the Colonic Mucus Barrier and Enhances Pathogen Susceptibility. Cell 167: 1339-1353 e1321.

83. Wolfe AJ (2015) Glycolysis for Microbiome Generation. Microbiol Spectr 3.

84. Cummings JH, Macfarlane GT (1991) The control and consequences of bacterial fermentation in the human colon. J Appl Bacteriol 70: 443-459.

85. den Besten G, van Eunen K, Groen AK, Venema K, Reijngoud DJ, et al. (2013) The role of short-chain fatty acids in the interplay between diet, gut microbiota, and host energy metabolism. J Lipid Res 54: 2325-2340.

86. Rios-Covian D, Ruas-Madiedo P, Margolles A, Gueimonde M, de Los Reyes-Gavilan CG, et al. (2016) Intestinal Short Chain Fatty Acids and their Link with Diet and Human Health. Front Microbiol 7: 185.

87. Zhu L, Baker SS, Gill C, Liu W, Alkhouri R, et al. (2013) Characterization of gut microbiomes in nonalcoholic steatohepatitis (NASH) patients: a connection between endogenous alcohol and NASH. Hepatology 57: 601-609.

88. Gkolfakis P, Dimitriadis G, Triantafyllou K (2015) Gut microbiota and non-alcoholic fatty liver disease. Hepatobiliary Pancreat Dis Int 14: 572-581.

89. Walldius G, Jungner I, Holme I, Aastveit AH, Kolar W, et al. (2001) High apolipoprotein B, low apolipoprotein A-I, and improvement in the prediction of fatal myocardial infarction (AMORIS study): a prospective study. Lancet 358: 2026-2033.

90. Jesch ED, Carr TP (2017) Food Ingredients That Inhibit Cholesterol Absorption. Prev Nutr Food Sci 22: 67-80.

91. Ribas SA, Cunha DB, Sichieri R, Santana da Silva LC (2015) Effects of psyllium on LDL-cholesterol concentrations in Brazilian children and adolescents: a randomised, placebo-controlled, parallel clinical trial. Br J Nutr 113: 134-141.

92. Knopp RH, Superko HR, Davidson M, Insull W, Dujovne CA, et al. (1999) Long-term blood cholesterol-lowering effects of a dietary fiber supplement. Am J Prev Med 17: 18-23.

93. Wolever TMS, Rahn M, Dioum EH, Jenkins AL, Ezatagha A, et al. (2021) Effect of Oat β-Glucan on Affective and Physical Feeling States in Healthy Adults: Evidence for Reduced Headache, Fatigue, Anxiety and Limb/Joint Pains. Nutrients 13: 1534.

94. Davidson MH, Dugan LD, Burns JH, Bova J, Story K, et al. (1991) The hypocholesterolemic effects of beta-glucan in oatmeal and oat bran. A dose-controlled study. JAMA 265: 1833-1839.

95. Jenkins DJ, Kendall CW, Vuksan V, Vidgen E, Parker T, et al. (2002) Soluble fiber intake at a dose approved by the US Food and Drug Administration for a claim of health benefits: serum lipid risk factors for cardiovascular disease assessed in a randomized controlled crossover trial. Am J Clin Nutr 75: 834-839.

96. Ho HVT, Jovanovski E, Zurbau A, Blanco Mejia S, Sievenpiper JL, et al. (2017) A systematic review and meta-analysis of randomized controlled trials of the effect of konjac glucomannan, a viscous soluble fiber, on LDL cholesterol and the new lipid targets non-HDL cholesterol and apolipoprotein B. Am J Clin Nutr 105: 1239-1247.

97. Tuomilehto J, Silvasti M, Aro A, Koistinen A, Karttunen P, et al. (1988) Long term treatment of severe hypercholesterolaemia with guar gum. Atherosclerosis 72: 157-162.

98. Jensen CD, Spiller GA, Gates JE, Miller AF, Whittam JH (1993) The effect of acacia gum and a water-soluble dietary fiber mixture on blood lipids in humans. J Am Coll Nutr 12: 147-154.

99. Haskell WL, Spiller GA, Jensen CD, Ellis BK, Gates JE (1992) Role of water-soluble dietary fiber in the management of elevated plasma cholesterol in healthy subjects. Am J Cardiol 69: 433-439.

100. Lairon D, Arnault N, Bertrais S, Planells R, Clero E, et al. (2005) Dietary fiber intake and risk factors for cardiovascular disease in French adults. Am J Clin Nutr 82: 1185-1194.

101. Ruottinen S, Lagstrom HK, Niinikoski H, Ronnemaa T, Saarinen M, et al. (2010) Dietary fiber does not displace energy but is associated with decreased serum cholesterol concentrations in healthy children. Am J Clin Nutr 91: 651-661.

102. Chiang JY (2013) Bile acid metabolism and signaling. Compr Physiol 3: 1191-1212.

103. Anderson TA, Redlin J (1973) Effect of dietary monosodium glutamate and cholesterol on growth and lipid metabolism in the rat. Proc Soc Exp Biol Med 143: 270-274.

104. Lipsky H, Gloger M, Frishman WH (1990) Dietary fiber for reducing blood cholesterol. J Clin Pharmacol 30: 699-703.

105. Vuksan V, Jenkins AL, Rogovik AL, Fairgrieve CD, Jovanovski E, et al. (2011) Viscosity rather than quantity of dietary fibre predicts cholesterol-lowering effect in healthy individuals. Br J Nutr 106: 1349-1352.

106. Jensen CD, Haskell W, Whittam JH (1997) Long-term effects of water-soluble dietary fiber in the management of hypercholesterolemia in healthy men and women. Am J Cardiol 79: 34-37.

107. Davidson MH, Dugan LD, Stocki J, Dicklin MR, Maki KC, et al. (1998) A low-viscosity soluble-fiber fruit juice supplement fails to lower cholesterol in hypercholesterolemic men and women. J Nutr 128: 1927-1932.

108. Heijnen ML, van Amelsvoort JM, Deurenberg P, Beynen AC (1996) Neither raw nor retrograded resistant starch lowers fasting serum cholesterol concentrations in healthy normolipidemic subjects. Am J Clin Nutr 64: 312-318.

109. Vega-Lopez S, Venn BJ, Slavin JL (2018) Relevance of the Glycemic Index and Glycemic Load for Body Weight, Diabetes, and Cardiovascular Disease. Nutrients 10: 1361.

110. Jenkins DJA, Dehghan M, Mente A, Bangdiwala SI, Rangarajan S, et al. (2021) Glycemic Index, Glycemic Load, and Cardiovascular Disease and Mortality. N Engl J Med 384: 1312-1322.

111. Ormazabal V, Nair S, Elfeky O, Aguayo C, Salomon C, et al. (2018) Association between insulin resistance and the development of cardiovascular disease. Cardiovasc Diabetol 17: 122.

112. Weickert MO, Pfeiffer AFH (2018) Impact of Dietary Fiber Consumption on Insulin Resistance and the Prevention of Type 2 Diabetes. J Nutr 148: 7-12.

113. Lu ZX, Walker KZ, Muir JG, O'Dea K (2004) Arabinoxylan fibre improves metabolic control in people with Type II diabetes. Eur J Clin Nutr 58: 621-628.

114. El Khoury D, Goff HD, Berengut S, Kubant R, Anderson GH (2014) Effect of sodium alginate addition to chocolate milk on glycemia, insulin, appetite and food intake in healthy adult men. Eur J Clin Nutr 68: 613-618.

115. Hartvigsen ML, Gregersen S, Laerke HN, Holst JJ, Bach Knudsen KE, et al. (2014) 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 68: 84-90.

116. Abutair AS, Naser IA, Hamed AT (2016) Soluble fibers from psyllium improve glycemic response and body weight among diabetes type 2 patients (randomized control trial). Nutr J 15: 86.

117. Ziai SA, Larijani B, Akhoondzadeh S, Fakhrzadeh H, Dastpak A, et al. (2005) Psyllium decreased serum glucose and glycosylated hemoglobin significantly in diabetic outpatients. J Ethnopharmacol 102: 202-207.

118. Williams JA, Lai CS, Corwin H, Ma Y, Maki KC, et al. (2004) Inclusion of guar gum and alginate into a crispy bar improves postprandial glycemia in humans. J Nutr 134: 886-889.

119. Larson R, Nelson C, Korczak R, Willis H, Erickson J, et al. (2021) Acacia Gum Is Well Tolerated While Increasing Satiety and Lowering Peak Blood Glucose Response in Healthy Human Subjects. Nutrients 13: 618.

120. Stewart ML, Wilcox ML, Bell M, Buggia MA, Maki KC (2018) Type-4 Resistant Starch in Substitution for Available Carbohydrate Reduces Postprandial Glycemic Response and Hunger in Acute, Randomized, Double-Blind, Controlled Study. Nutrients 10: 129.

121. Arias-Córdova Y, Ble-Castillo JL, García-Vázquez C, Olvera-Hernández V, Ramos-García M, et al. (2021) Resistant Starch Consumption Effects on Glycemic Control and Glycemic Variability in Patients with Type 2 Diabetes: A Randomized Crossover Study. Nutrients 13: 4052.

122. Blackburn NA, Redfern JS, Jarjis H, Holgate AM, Hanning I, et al. (1984) The mechanism of action of guar gum in improving glucose tolerance in man. Clin Sci (Lond) 66: 329-336.

123. Luhovyy BL, Mollard RC, Yurchenko S, Nunez MF, Berengut S, et al. (2014) The effects of whole grain high-amylose maize flour as a source of resistant starch on blood glucose, satiety, and food intake in young men. J Food Sci 79: H2550-2556.

124. Miranda PM, Horwitz D (1978) High-fiber diets in the treatment of diabetes mellitus. Ann Intern Med 88: 482-486.

125. Alam NH, Meier R, Rausch T, Meyer-Wyss B, Hildebrand P, et al. (1998) Effects of a partially hydrolyzed guar gum on intestinal absorption of carbohydrate, protein and fat: a double-blind controlled study in volunteers. Clin Nutr 17: 125-129.

126. Wolever TMS, Tosh SM, Spruill SE, Jenkins AL, Ezatagha A, et al. (2020) Increasing oat β-glucan viscosity in a breakfast meal slows gastric emptying and reduces glycemic and insulinemic responses but has no effect on appetite, food intake, or plasma ghrelin and PYY responses in healthy humans: a randomized, placebo-controlled, crossover trial. Am J Clin Nutr 111: 319-328.

127. Liu J, Lu W, Liang Y, Wang L, Jin N, et al. (2022) Research Progress on Hypoglycemic Mechanisms of Resistant Starch: A Review. Molecules 27: 7111.

128. Pugh JE, Cai M, Altieri N, Frost G (2023) A comparison of the effects of resistant starch types on glycemic response in individuals with type 2 diabetes or prediabetes: A systematic review and meta-analysis. Front Nutr 10: 1118229.

129. Al-Mana NM, Robertson MD (2018) Acute Effect of Resistant Starch on Food Intake, Appetite and Satiety in Overweight/Obese Males. Nutrients 10: 1993.

130. Slavin JL, Green H (2007) Dietary Fibre and Satiety. Nutrition Bulletin 32: 11.

131. Rebello CJ, O'Neil CE, Greenway FL (2016) Dietary fiber and satiety: the effects of oats on satiety. Nutr Rev 74: 131-147.

132. Howarth NC, Saltzman E, Roberts SB (2001) Dietary fiber and weight regulation. Nutr Rev 59: 129-139.

133. van de Vijver LP, van den Bosch LM, van den Brandt PA, Goldbohm RA (2009) Whole-grain consumption, dietary fibre intake and body mass index in the Netherlands cohort study. Eur J Clin Nutr 63: 31-38.

134. Tucker LA, Thomas KS (2009) Increasing total fiber intake reduces risk of weight and fat gains in women. J Nutr 139: 576-581.

135. Kelly RK, Calhoun J, Hanus A, Payne-Foster P, Stout Ret al. (2023) Increased dietary fiber is associated with weight loss among Full Plate Living program participants. Front Nutr 10: 1110748.

136. Clark MJ, Slavin JL (2013) The effect of fiber on satiety and food intake: a systematic review. J Am Coll Nutr 32: 200-211.

137. Guerin-Deremaux L, Pochat M, Reifer C, Wils D, Cho S, et al. (2011) The soluble fiber NUTRIOSE induces a dose-dependent beneficial impact on satiety over time in humans. Nutr Res 31: 665-672.

138. Akyol A, Dasgin H, Ayaz A, Buyuktuncer Z, Besler HT (2014) β-Glucan and dark chocolate: a randomized crossover study on short-term satiety and energy intake. Nutrients 6: 3863-3877.

139. Calame W, Thomassen F, Hull S, Viebke C, Siemensma AD (2011) Evaluation of satiety enhancement, including compensation, by blends of gum arabic. A methodological approach. Appetite 57: 358-364.

140. Kovacs EM, Westerterp-Plantenga MS, Saris WH, Goossens I, Geurten P, et al. (2001) The effect of addition of modified guar gum to a low-energy semisolid meal on appetite and body weight loss. Int J Obes Relat Metab Disord 25: 307-315.

141. Parnell JA, Reimer RA (2009) Weight loss during oligofructose supplementation is associated with decreased ghrelin and increased peptide YY in overweight and obese adults. Am J Clin Nutr 89: 1751-1759.

142. Chambers ES, Morrison DJ, Frost G (2015) Control of appetite and energy intake by SCFA: what are the potential underlying mechanisms? Proc Nutr Soc 74: 328-336.

143. Rao TP, Hayakawa M, Minami T, Ishihara N, Kapoor MP, et al. (2015) Post-meal perceivable satiety and subsequent energy intake with intake of partially hydrolysed guar gum. Br J Nutr 113: 1489-1498.

144. da Silva MVT, Nunes SS, Costa WC, Sanches SMD, Silveira ALM, et al. (2022) Acute intake of fructooligosaccharide and partially hydrolyzed guar gum on gastrointestinal transit: A randomized crossover clinical trial. Nutrition 102: 111737.

145. Poutanen KS, Dussort P, Erkner A, Fiszman S, Karnik K, et al. (2017) A review of the characteristics of dietary fibers relevant to appetite and energy intake outcomes in human intervention trials. Am J Clin Nutr 106: 747-754.

146. Aliyu AI, Nixon A, Hoad CL, Marciani L, Corsetti M, et al. (2023) A comparative, randomised MRI study of the physiological and appetitive responses to gelling (alginate) and non-gelling nasogastric tube feeds in healthy men. Br J Nutr 130: 1316-1328.

147. McRorie JW, Daggy BP, Morel JG, Diersing PS, Miner PB, et al. (1998) Psyllium is superior to docusate sodium for treatment of chronic constipation. Aliment Pharmacol Ther 12: 491-497.

148. Major G, Murray K, Singh G, Nowak A, Hoad CL, et al. (2018) Demonstration of differences in colonic volumes, transit, chyme consistency, and response to psyllium between healthy and constipated subjects using magnetic resonance imaging. Neurogastroenterol Motil 30: e13400.

149. Murray K, Wilkinson-Smith V, Hoad C, Costigan C, Cox E, et al. (2014) Differential effects of FODMAPs (fermentable oligo-, di-, mono-saccharides and polyols) on small and large intestinal contents in healthy subjects shown by MRI. Am J Gastroenterol 109: 110-119.

150. Canani RB, Costanzo MD, Leone L, Pedata M, Meli R, et al. (2011) Potential beneficial effects of butyrate in intestinal and extraintestinal diseases. World J Gastroenterol 17: 1519-1528.

151. Marteau P, Jacobs H, Cazaubiel M, Signoret C, Prevel JM, et al. (2011) Effects of chicory inulin in constipated elderly people: a double-blind controlled trial. Int J Food Sci Nutr 62: 164-170.

152. Chan TC, Yu VMW, Luk JKH, Chu LW, Yuen JKY, et al. (2022) Effectiveness of Partially Hydrolyzed Guar Gum in Reducing Constipation in Long Term Care Facility Residents: A Randomized Single-Blinded Placebo-Controlled Trial. J Nutr Health Aging 26: 247-251.

153. U.S. Food and Drug Administration. 2016c. 21 CFR 1010.77 Health Claims: Fruits, Vegetables, and Grain Products That Contain Fiber, Particularly Soluble Fiber, and Risk of Coronary Heart Disease.

154. U.S. Food and Drug Administration. 2016b. 21 CFR 101.81 Health Claims: Soluble Fiber From Certain Foods and Risk of Coronary Heart Disease (CHD).

155. EFSA Panel on Dietetic Products N, Allergies. 2010b. Scientific Opinion on the substantiation of health claims related to dietary fibre (ID 744, 745, 746, 748, 749, 753, 803, 810, 855, 1415, 1416, 4308, 4330) pursuant to Article 13(1) of Regulation (EC) No 1924/2006. EFSA Journal 8: 1735.

156. Scientific Advisory Committee on Nutrition. (2015) SACN Carbohydrates and Health Report. London: The Stationery Ofiice Limited.

157. Ministry of Health of the People's Republic of China. (2008) GB/Z 21922-2008 Fundamental Terminology and Definition of Nutritional Component in Foods.

158. Xiang X, Zhu J (2022) Scientific Consensus on the Definition and Source of Dietary Fiber. Acta Nutrimenta Sinica 44: 5.

159. Wang SS, Lay S, Yu HN, Shen SR (2016) Dietary Guidelines for Chinese Residents (2016): comments and comparisons. J Zhejiang Univ Sci B 17: 649-656.

160. National Institute of Nutrition India. (2011) Dietary Guidelines for Indians - A Manual. Hyderabad: National Institute of Nutrition.

161. Schönenberger KA, Huwiler VV, Reber E, Mühlebach S, Stanga Z, et al. (2024) Dietary fibre intake and its association with ultraprocessed food consumption in the general population of Switzerland: analysis of a population-based, cross-sectional national nutrition survey. BMJ Nutr Prev Health 7: 26-37.

162. McKeown NM, Fahey GC Jr, Slavin J, van der Kamp JW (2022) Fibre intake for optimal health: how can healthcare professionals support people to reach dietary recommendations? Bmj 378: e054370.