

# The Effects of Dietary Fiber on Metabolic Health and Gut Microbiota

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## Abstract:

Glucolipid metabolic disorders (GLMD) are fast-going health concerns worldwide. There is a growing interest in researching nutritional approaches that can enhance human health and it is commonly known that dietary fiber has prebiotic effects. This paper investigates the relationship between dietary fiber and GLMD, with a focus on obesity and type 2 diabetes. Dietary fiber mechanisms in modulating glucolipid metabolism. Specifically, it examines DF's role in regulating glycemic levels and lipid metabolism. Also, five separated experiments conducted on healthy adults are listed to show the relationships between dietary fiber and short-chain fatty acids (SCFAs) production. The findings underscore dietary fiber's potential as a therapeutic intervention for mitigating GLMD by multiple pathways, including improving insulin sensitivity, promoting satiety, and modulating gut microbiota. Overall, the insights provided in this review contribute to a deeper understanding of dietary fiber's therapeutic potential and pave the way for future research and applications in the field of metabolic disorders.

**Keywords:** Glucolipid Metabolic Disorders; Dietary Fiber; Glycemic Regulation; Lipid Metabolism; Gut Microbiota.

## 1. Introduction

Dietary Fiber (DF) is made up of lignin and complex, nonstarch carbohydrates that cannot be broken down into their component monomers in the small intestine by mammals. It is thought to provide no calories, yet humans and other mammals use the metabolites that the bacteria in our colon create to meet their energy needs [1]. Based on its solubility, DF can be categorized by insoluble dietary fiber (IDF) and soluble dietary fiber (SDF). IDF includes lignin, cellulose and some hemicellulose. SDF includes oligosaccharides and some indigestible polysaccharides.

A number of reasons, such as changes in our eating habit, satiation, and low energy expenditure, can cause imbalances between our energy intake and expenditure. Through a variety of pathways, the gut microbiota (GM) greatly influence every facet of energy balance [2]. One significant class of bio-products created by the GM is short chain fatty acids (SCFAs), which are mostly obtained through the fermentation of non-digestible carbohydrates, such as DF, which the GM can use [3].

In this study, the effects of DF on GM and further influence on SCFAs are discussed. Also, the mechanism of DF mitigating two typical Glucolipid metabolic disorders (obesity and diabetes) are explained clearly.

## 2. Glucolipid Metabolic Disorders

The prevalence of glucolipid metabolic disorders (GLMD)

is rising significantly with the change of lifestyle, posing threats to human wellbeing and causing clinical problems worldwide. Dysregulation of lipids and glucose metabolism can bring many types of metabolic diseases, including diabetes, obesity, NAFLD, and atherosclerotic cardiovascular disease (CAD).

The damage resulting from persistently abnormal blood sugar and lipid levels to the body's organs is what causes the disorder of glucose and lipid metabolism, since it causes a progressive reduction in the organs' ability to function. In addition, it is believed that both microvascular and macrovascular damage have a significant role in patient death and disability [4]. Currently, numerous metabolic illnesses cannot be adequately controlled by a single intervention for hyperglycemia or hyperlipidemia, leading to inadequate blood sugar management and unsatisfactory lipid control.

A variety of metabolic organ disorders can lead to the complicated disease known as the disorder of glucose and lipid metabolism. Interactions between fundamental pathogenic mechanisms such dysregulation of the GM, oxidative stress, insulin resistance, neuroendocrine axis dysfunction, and chronic inflammatory response play a role in the pathogenesis of various disorders. These diseases occur and evolve as a result of the aforementioned procedures.

### **3. The Regulations of DF on Health**

#### **3.1 Regulate Glycemic Level and Lipid Metabolism**

Studies conducted over a brief period have revealed a correlation between the viscosity of hydrated fiber and the effectiveness of SDF in the metabolism of glucose and insulin. Numerous short-term clinical trials have proved that using a viscous, soluble fiber supplement with meals, such as gel-forming fibers, improves glycemic control, and reducing fasting plasma levels of insulin, glucose, and HbA1c, [5]. Using an SDF supplement to improve glycemic control involves a dose-dependent, substantial increase in the chyme's viscosity [6]. Viscosity can cause the stomach to empty more slowly, slow down the glucose absorption, and cause the unstirred layer's viscosity to grow [7]. Viscosity's impact on glucose release was investigated using a carefully monitored *in vitro*. The results showed that the maltodextrin to glucose conversion decreased by 35% when the bolus viscosity increased 1-15 mPa·s [8].

The augmentation of viscosity results in a deceleration of nutrient breakdown into constituents viable for absorption at the brush boundary. Consequently, the presence of SDF induces a denser chyme, impeding the process of digestion and absorption. This alteration redirects nutrients that would typically undergo absorption at the initial segment of the small intestine towards the distal ileum, where their presence is usually minimal. Mucosal L cells within the distal ileum can trigger the release of GLP-1 into the bloodstream upon nutrient administration. GLP-1 linked to decreased hunger, increased development of pancreatic beta cells, enhanced insulin sensitivity and production, and decreased release of glucagon. In addition to having an impact on food intake and digestion, the distal ileum's macronutrient content can also trigger the ileal brake phenomenon, which is mediated by YY and GLP-1. By effectively delaying small bowel transit and stomach emptying, the ileal brake phenomenon can reduce the amount of nutrients lost to the large intestine [9,10].

The effect of DF on lowering blood cholesterol levels has drawn more attention lately. Through a number of mechanisms, such as bile binding, viscosity, and small intestinal bulking, DF affects lipid levels in the blood and the liver. These mechanisms increase the synthesis of SCFAs and alter genes linked to lipid metabolism, but they also inhibit the absorption of glucose and fats. DFs have the potential to serve as alternative supplements to promote health, particularly in lowering lipid levels in humans. However, further clinical evidence is necessary to bolster this proposition, and a deeper understanding of the underlying mechanism is still required. Only by fully comprehending the mechanism and dosage relationship of each type of

DF can then be effectively applied in the intervention of hyperlipidemic patients [11].

#### **3.2 Regulate GM Composition and SCFAs Production**

Valeric, isovaleric, and hexanoic acids were found to decrease after six weeks of supplementing with 15g/day of arabinogalactan in a study involving thirty healthy persons. In contrast to the placebo group, there was no discernible variation in SCFAs or isobutyrate levels. The microbiota composition and  $\alpha$ -diversity of the Arabinogalactan intervention group were substantially lower than those of the placebo group after adjusting for respective baselines at weeks 3 and 6. However, at weeks three and six, there were no discernible variations in the two groups'  $\beta$ -diversity measurements from the baseline. Due to a considerable increase in bacteroidetes and a significant decrease in firmicutes, the treatment group's firmicutes/Bacteroidetes ratio was significantly lowered. Furthermore, when provided arabinogalactan, bifidobacteria tended to grow in comparison to the placebo group. The researchers used PICRUSt to foresee an overrepresentation of  $\alpha$ -L-rhamnosidase, which may liberate rhamnose from polysaccharides like arabinogalactan proteins in the intervention group [12].

Only one of the chosen trials used HPLC to assess how GOS affected fecal SCFAs. Over the course of four weeks, 24 healthy persons took 21.6 g/day of GOS; no discernible changes in SCFAs, isobutyrate, or succinate were seen, either in comparison to baseline or to MD. After four weeks of GOS administration, there was a significant decrease in bacterial diversity. Similarly, following 4 weeks of treatment,  $\beta$ -diversity measurements revealed notable alterations in the organization of the GM. The authors' taxonomic analysis revealed a noteworthy rise in bifidobacteria, which qPCR verified [13].

In a trial involving dose-response, forty individuals in good health were given three structurally different types-IV resistant starches (RS4s) to gradually raise their daily intake of tapioca, maize, or potato RS4 to 10, 20, 35, or 50 g. Generally speaking, RS4 supplementation had no influence on the total SCFA concentration in feces; yet, certain RS4s had varying effects on specific SCFAs. The concentration of butyrate were considerably higher in maize RS4 compared to baseline; a decrease in propionate's relative proportion and the ratio of BCFA to SCFAs was also noted. Propionate increased considerably from baseline when tapioca RS4 was administered at a dose of 35 g/day; this increase was also greater than that of maize RS4. In a manner similar to maize RS4, 35 g/day of tapioca RS4 consumption was linked to a decrease in the ratio of BCFA to SCFAs when contrasted with both potato RS4 and a placebo. Fascinatingly, a dose-response

connection was also noted in this trial, with a plateau at 35 g. Using 16S rRNA sequencing to assess the GM, greater doses of tapioca and maize RS4s led to a decrease in  $\alpha$ -diversity. Rather, the composition was affected in a unique and nearly substrate-specific way. More precisely, maize RS4 led to the enrichment of butyrate-producing bacteria such as *E. rectale*, *Oscillibacter* spp., *Ruminococcus* spp., and *Anaeromassilibacillus* spp., while tapioca RS4 enriched *P. distasonis*, *F. prausnitzii*, and *Eisenbergiella* spp. Spearman's correlation analysis revealed that changes in butyrate proportions induced by maize RS4 were positively correlated with an increase in *E. rectale* and changes in propionate proportions induced by tapioca RS4 were positively correlated with an increase in *P. distasonis*, confirming the close relationships between compositional and functional changes [14].

In a separate study, 19 participants were administered 40 g of high-amylose RS2 for a duration of 4 weeks, resulting in a significantly elevated serum acetate level compared to the control group, as assessed by GC. Additionally, changes in acetate levels were positively correlated with postprandial GLP-1 alterations observed after 30 minutes. Analysis of GM through 16S rRNA sequencing unveiled several significant alterations. These include an elevation in *Ruminococcaceae\_UCG-005* and a reduction in *Bacteroides*, *Holdemanella*, *Coprococcus\_1*, *Coprococcus\_3*, *Lachnospirillum*, *Erysipelotrichaceae\_UCG-003*, *Paraprevotella*, *Phascolarctobacterium*, and *Eubacterium\_eligens* group. These findings are consistent with prior research and may elucidate the advantages of resistant starch (RS) [15].

Finally, consuming 30 g/day of RS for three months did not significantly change the amount of SCFAs in the feces, as determined by GC, according to a study done on 42 middle-aged adults. By employing 16S rRNA sequencing to analyze the compositional structure of the GM, the authors noted alterations. They found that  $\alpha$ -diversity had decreased, that *R. bromii*, which is crucial to the early breakdown of RS and may benefit bifidobacteria in the future, and *Bifidobacterium* (particularly *B. ruminantium*) had increased in relative abundance, and that *R. torques*, a species that breaks down mucus, had decreased [16].

### 3.3 Relieve Metabolism Disorder Induced Problems in the Body

#### 3.3.1 DF and obesity

By controlling food consumption, digestion, absorption, and metabolism, DF can prevent fat absorption and lower energy intake. The high viscosity of SDF, can impede the movement of nutrients. DF's primary mechanism for losing weight consists of the following: 1) Its structure, galacturonic acid, has a high viscosity. Furthermore, DF has high CAC, OHC, and WHC, all of which can enhance

fat adsorption. Sticky pectin, which is present in broccoli DF, is said by Mandimika et al. to improve the excretion of cholesterol and bile acid from the enterohepatic circulation and to decrease the consumption of fat in food [17]. IDF can bind or adsorb bile acids and cholesterol, lowering cholesterol in various pools [18]. 2) DF has a high WSC, which is proven to increase fullness and decrease food intake. According to Lambert et al., eating DF increases satiety and promotes water absorption, which may delay nutrient absorption and reduce energy intake [19]. 3) DF stimulates the release of PYY and GLP-1 and produces SCFAs through gut microbial fermentation. Intestinal L-cells secrete GLP-1, which controls muscle cell glycogen synthesis, promotes satiety, and improves pancreatic cell development and insulin production [20]. Pear pomace's IDF has been shown to have the ability to dilute energy, improve energy utilization, and trigger the production of GLP-1 and PYY after intestinal fermentation. These actions ultimately reduce fat cells and considerably improve obesity [21]. All in all, DF's effectiveness in reducing obesity primarily stems from its various physicochemical characteristics, leading to delayed fat absorption from food. SDF and IDF both contribute to diminishing obesity, a goal that necessitates extensive experimental studies.

#### 3.3.2 DF and diabetes

Over recent decades, the prevalence of diabetes, notably type 2, has surged, comprising 90% of all cases. This escalation has been rapid, witnessing a steady increase in the global diabetic population, from 151 million in 2000 to 285 million in 2010. Projections indicate that by 2030, the prevalence of diabetes is estimated to reach 7.8% [22]. Then the mechanism of DF about its function of lowering blood glucose. First, the diffusion of glucose might encounter hindrance due to a physical impediment created by the topology of DF. Fibrous particles form a barrier that physically obstructs the entry of glucose molecules into the network. As the structure of DF loosens, with increased exposure of surface functional groups, the interaction between DF and glucose intensifies, thereby enhancing GAC [22]. Studies by Ashutosh et al. and Sri-chamroen et al. claim that DF made from sunflower, tamarind, and cassia seeds inhibits the diffusion of glucose [23, 24]. Furthermore, DF that isolated from potatoes significantly slows the diffusion of glucose [25]. It is because of DF's porosity and surface functional group exposure that the interaction between DF and glucose is improved. Because of its physical barrier, millet IDF can assist better manage blood glucose levels by delaying the absorption of glucose. Second, viscous fibers can delay gastric emptying and enhance sensitivity to the hypoglycemic effects of insulin. Guar gum's viscosity helps lessen postprandial

hyperglycemia. Third, the GM ferments DF to create SCFAs, which in turn triggers the release of satiety hormones (GLP-1 and PYY), which aid in raising insulin secretion and regulating blood glucose levels [26]. Also, Butyric and acetic acids can enhance glucose homeostasis by promoting intestinal synthesis of GLP-1 and PYY [27].

## 4. Future Perspectives and Applications

In addition to the direct effects of DFs on hyperlipidemia, there is a growing interest in site-specific drug delivery systems utilizing polysaccharides such as gum, pectin, inulin, and konjac glucomannan. These approaches have the potential to reduce side effects and enhance the bioavailability of drugs at specific target sites. For instance, a study demonstrated the potential of utilizing ultrafine redispersible spray-dried emulsion with pectin as a carrier for delivering atorvastatin calcium, a commonly used medication for hyperlipidemia. This approach shows promise for improving the antihyperlipidemic effects of the drug [28]. Pharmacological and pharmaceutical assessments suggest that this strategy could be effectively utilized for liver-targeted drug delivery.

Nevertheless, DF studies have several drawbacks as well. First off, DF's varying degrees of polymerization—particularly the fact that DF derived from various sources has varying degrees of polymerization—may help prevent a variety of ailments. Given that the degree of polymerization of DFs remains poorly elucidated in terms of disease prevention mechanisms, exploring the structure of DFs with different degrees of polymerization is crucial for further research on disease prevention. Second, the diseases that DF prevents are not just the ones that are covered in this review. Specifically, a great deal of experimental research is needed to control the GM in order to prevent and treat various diseases. Third, the type and amount of DF consumed will affect illness prevention and treatment. It is crucial to explore both the dosage and type of fiber in disease prevention and treatment. DF will be more helpful in preventing and treating human diseases as well as advancing human health once the aforementioned issues are resolved.

## 5. Conclusion

DF can help with glucolipid metabolic disorders by regulating glycemic levels and lipid metabolism. SDF like psyllium and guar gum possess the capability to enhance glycemic management and reduce blood cholesterol levels by modulating various metabolic pathways. Research indicates a positive correlation between DF intake and favorable alterations in GM composition, as well as increased production of SCFAs. The supplementation of arabinogalactan resulted in a decrease in microbiota

composition  $\alpha$ -diversity, characterized by a drop in the abundance of Bacteroides and Blautia, and an increase in Genera Eisenberguella and Howardella. The supplementation with GOS did not significantly alter SCFA levels in feces. However, it led to a decrease in bacterial diversity, particularly a decrease in the abundance of Bacteroides, Blautia, and Lachnospiraceae members such as Lachnospiraceae\_UCG-004 and Lachnoclostridium. Supplementation with different types of resistant starches (RS4s) showed varying effects on SCFA concentrations. While RS4s did not affect total SCFA concentration, they led to changes in individual SCFA levels. For example, maize RS4 led to increased butyrate production, while tapioca RS4 increased propionate levels. A study with 19 participants who received high-amylose resistant starch (RS2) supplementation showed increased serum acetate levels. Supplementation with unmodified potato resistant starch (RS) did not significantly alter SCFA levels in feces. However, it led to changes in GM composition, characterized by a decline in bacterial diversity and changes in the abundance of specific taxa.

The physicochemical properties of DF, including WHC and fermentability, play crucial roles in alleviating metabolic disorder-induced problems such as obesity and diabetes. DF consumption leads to reduced calorie intake and increased satiety, contributing to weight loss. Some types of DF, especially IDF, add bulk to the diet without adding calories. This increases fullness without energy intake, which may help prevent overeating and weight gain. Beneficial bacteria flourish in the gut when DF is present, and this helps improve insulin sensitivity and metabolism. For those with type 2 diabetes, a healthy gut microbiome is linked to improved blood sugar regulation and a lower risk of complications.

However, further research is needed to optimize DF interventions, including understanding the underlying mechanisms, optimizing dosage and fiber types, and exploring novel delivery systems for enhanced efficacy in managing GLMD. These findings underscore the potential of DF as a comprehensive approach to addressing GLMD and improving metabolic health globally.

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