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Research Progress on the Synergy Mechanism of Dietary Fiber and Prebiotics

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ABSTRACT

As a chronic disease seriously affecting human health, diabetes has seen a significant upward trend in global incidence. Data reported by the International Diabetes Federation (IDF) indicates that the quantity of diabetic individuals around the world has exceeded 500 million. Within China, the prevalence rate of diabetes has surpassed 12%, and nearly 35% of the adult population are in the pre-diabetic stage, indicating an extremely severe situation. Dietary fiber and prebiotics offer numerous benefits to human health, and their synergistic effects have garnered extensive attention in recent years. This article synthesizes relevant studies to elaborate on the definitions and classifications of dietary fiber and prebiotics, and details the impacts and mechanisms of their individual and synergistic actions on gut microbiota, intestinal barrier function, metabolic regulation, immune regulation, and other aspects. Dietary fiber can be processed by gut microbiota to boost the proliferation of friendly bacteria and regulate the intestinal barrier; prebiotics may specifically trigger the multiplication of good bacteria. Their synergistic effects demonstrate more significant outcomes than individual actions in regulating gut microecology, improving metabolic diseases, enhancing immunity, etc., providing a theoretical basis for promoting human health through dietary interventions.

KEYWORDS

Dietary fiber; Prebiotics; Synergistic effect; Gut microbiota; Metabolic regulation

1. INTRODUCTION

Diabetes refers to a category of metabolic disorders. It is marked by long - term high blood sugar levels, which are triggered by various causes, is a serious threat to global human health. Its pathogenesis stems mainly from defective secretion and/or actions of insulin [1]. In recent years, The incidence of global diabetes mellitus is on a significant upward trend. Data released by the International Diabetes Federation (IDF) is concerning: the number of diabetic patients worldwide has continued to grow and has already exceeded 500 million [2]. In China, the situation is equally worrying, with the prevalence of diabetes exceeding 12% and still increasing steadily each year. More critically, the pre-diabetic population is enormous, accounting for nearly 35% of the adult population [3]. Diabetes not only seriously impairs patients' quality of life and induces multiple chronic concurrent conditions in various tissues and parts of the body, including the eyes, kidneys, nervous system, heart, and blood vessels—resulting in functional degradation or even organ failure—but also brings about a substantial socioeconomic burden. Consequently, it is urgent to explore effective solutions for the prevention and control of diabetes mellitus.

Meanwhile, with increasing attention to healthy diets and nutritional health, dietary fiber and prebiotics have become research hotspots due to their potential benefits for human health. Critical role of dietary fiber in regulating intestinal tract functionality, blood glucose, blood lipids and more, while prebiotics can selectively stimulate the development and the activity of useful microorganisms in the intestinal tract [4]. For the last few years, increasingly, research is focusing on the synergistic role of dietary fiber and prebiotics, finding that their combination demonstrates more significant effects in improving gut microecology and promoting health than either alone. In-depth exploration of their synergistic mechanism is of vital significance for optimizing dietary structures, developing functional foods, and preventing and treating related diseases including diabetes.

2. THE "INTESTINAL LEAKAGE" PHENOMENON IN DIABETIC PATIENTS

Diabetic patients frequently experience the "intestinal leakage" phenomenon, which is characterized by impaired intestinal barrier function and heightened intestinal permeability. In people with diabetes 2 mellitus (T2DM), research has found that serum zona occludens (ZO)-1, indicating increased intestinal permeability and the existence of "intestinal leakage" [5]. High-concentration glucose molecules can inhibit intestinal tight junctions and accelerate the destruction of the intestinal barrier, allowing dietary antigens, immune stimulants, and other substances in the intestine to easily enter the bloodstream, triggering systemic inflammation and autoimmune processes, leading to destruction of pancreatic islet β cells and exacerbating diabetes [6]. Dysbiosis of the intestinal microbiota impairs the intestinal barrier, enhance intestinal permeability, and trigger "intestinal leakage". Meanwhile, "intestinal leakage" further aggravates gut microbiota dysregulation [7]. In T2DM patients, gut microbiota dysregulation causes excessive absorption of short-chain fatty acids (SCFAs) and bile acids through the damaged intestinal barrier, leading to increased serum concentrations of total SCFAs and certain bile acids [8]. Type 1 diabetes mellitus (T1DM) patients also exhibit "intestinal leakage" caused by intestinal barrier damage. Research has shown that in populations at risk for T1DM, the microbiota of the gut in young adulthood varies considerably depending on geographic location. Alterations in gut microbiota may affect barrier function of the intestine and contribute to the pathogenesis of T1DM [7]. Impaired bowel barrier integrity can trigger the activation of islet-reactive T cells and lead to autoimmune diabetes. Additionally, "intestinal leakage" may facilitate autoimmune responses during the onset and progression of T1DM [9].

Due to the pivotal roles of gut microbiota and intestinal barrier function in the interpretation of the cause and progression of DM, establishing a scientific and effective evaluation system for these factors in diabetic patients is of substantial clinical significance. This evaluation system not only helps deepen the understanding of the pathogenesis of diabetes but also provides a strong basis for clinicians to assess the progression and prognosis of diabetic patients.

3. OVERVIEW OF DIETARY FIBER AND PREBIOTICS

3.1. Definition and Categorization of Dietary Fiber

With the deepening of research, the dictionary definition of dietary fiber has been continuously refined. Physiologically, the American Association of Cereal Chemists (AACC) defines it as the aggregate of edible plant components, carbohydrates, and analogous substances that resist digestion or absorption in the small intestine but undergo partial or complete fermentation in the colon. This includes polysaccharides, cellulose, hemicellulose, oligosaccharides, pectin, gum, wax, lignin, etc. [10]. According to its solubility, dietary fiber can be divided into water-soluble dietary fiber (such as pectin, inulin, β-glucan, etc.) and insoluble dietary fiber (such as cellulose, hemicellulose, lignin, etc.).Water-soluble dietary fiber can form a gel in water, delay gastric emptying, and decrease the pace of blood glucose elevation after a meal; insoluble dietary fiber mainly increases fecal volume and promotes intestinal peristalsis.

3.2. Definition and Common Types of Beneficial Antibiotics

The probiotic concept was initially put forward by Gibson and Roberfroid in 1995, describing components that can selectively stimulate the development and movement of useful bacteria in the colon, thus exerting beneficial effects on the host [11]. Fructooligosaccharides (FOS), galactooligosaccharides (GOS), inulin, and resistant dextrin are among the typical prebiotics. Fructooligosaccharides can promote the proliferation of Bifidobacteria, galactooligosaccharides can enhance the activity of Lactobacillus, and resistant dextrin can withstand gastric acid and reach the colon for fermentation. Studies have shown that daily intake of 5 grams of prebiotics can significantly improve gut microbiota balance [12].

4. REGULATORY IMPACTS OF DIETARY FIBER ALONG WITH PREBIOTICS ON THE ENTERIC MICROBIOTA

4.1. Impacts of Dietary Fiber on the Enteric Microbiota

Upon entering the intestine, dietary fiber is not susceptible to breakdown by the body's own digestion enzymes but acts as a fermentation substrate for gut microbiota. Various types of dietary fiber selectively influence on the composition of the enteric microbiota. For instance, Martinez et al. discovered that type 2 and type 4 resistant starches can increase the number of good bacteria like Bifidobacterium and Lactobacillus in human feces [13]. Water-soluble dietary fibers, including pectin and inulin, undergo fermentation by gut microbes, yielding short-chain fatty acids (SCFAs), such as acetic acid, propionic acid, and butyric acid [14]. These SCFAs not only provide energy to the cells of the gut, but also regulate gut pH, inhibit the development of harmful bacteria and promote the development of good bacteria such as bifidobacteria and lactic acid bacteria. Although insoluble dietary fiber is not heavily fermented by microbes, it increases the volume of intestinal contents and promotes peristalsis, helping maintain normal intestinal physiological functions and microbial community stability.

4.2. Influences of Prebiotics on Gut Microbiota

Prebiotics are selectively utilized by specific beneficial microorganisms in the intestine . For instance, fructooligosaccharides (FOS) are specifically fermented by Bifidobacterium, promoting its massive proliferation and restraining the proliferation of bad bacteria like E.coli and Clostridium, thereby altering gut microbiota composition and optimizing the intestinal microecological environment [15]. A person intervention study conducted by Ramnani et al. demonstrated that fruit and vegetable juice supplemented with Jerusalem artichoke inulin significantly elevated the abundance of Bifidobacterium in the intestine, exerting prebiotic effects [16]. SCFAs produced by prebiotic fermentation lower intestinal pH, creating an environment unfavorable for harmful bacteria, while stimulating intestinal mucosal cell proliferation and enhancing intestinal barrier function.

4.3. Mechanisms of Synergistic Regulation of Gut Microbiota by Dietary Fiber and Prebiotics

When dietary fiber and prebiotics coexist, they exhibit synergistic effects in regulating gut microbiota: dietary fiber provides a broad range of fermentation substrates for gut microbiota and creates a suitable living environment, while prebiotics accurately stimulate the development and movement of good bacteria [17]. Studies have shown that combined intervention with inulin and FOS increases the abundance of Akkermansia (a mucus-degrading bacterium) and improves intestinal barrier function (ZO-1 protein expression ↑30%) [18, 19]. This synergy is achieved through "cross-feeding": primary fermenting bacteria (e.g., Bacteroides) decompose fiber to produce intermediates (e.g., succinate), which are further utilized by Bifidobacterium to increase butyric acid production. This synergistic effect enhances the quantity and activity of beneficial bacteria, maintaining gut microecological stability and balance, effectively inhibiting harmful bacteria, and optimizing gut microbiota structure.

5. EFFECTS OF DIETARY FIBER AND PREBIOTICS ON INTESTINAL BARRIER FUNCTION

5.1. Usefulness of Dietary Fiber in Bowel Barrier Function

Dietary fiber is vital for maintaining intestinal barrier features. On one hand, short-chain fatty acids (SCFAs) generated through dietary fiber fermentation—especially butyric acid—promote binding of closely linked proteins for assembly in enteric epithelial cells. Through activation of the AMP - activated protein kinase (AMPK) signaling way, these SCFAs strengthen intercellular tight junctions, thereby decreasing intestinal permeability. Peng et al. revealed in a Caco-2 cell monolayer model that butyric acid enhances the extrudation of tight junction proteins ZO-1 and Occludin, thereby reinforcing the intestinal barrier [20]. On the other hand, dietary fiber promotes intestinal mucus secretion, and the mucus layer acts as a structural barrier to prevent pathogens and harmful substances from directly contacting the intestinal mucosa . Insoluble dietary fiber indirectly protects intestinal barrier function by increasing fecal volume, promoting peristalsis, and reducing the residence time of harmful substances in the intestine.

5.2. Usefulness of Prebiotics in Bowel Barrier Function

The modulation of gut microbiota by prebiotics leads to indirect influences in bowel barrier function. Prebiotics facilitate the proliferation of beneficial bacteria such as Bifidobacterium, which improve intestinal mucosal integrity and decrease intestinal permeability.The researches show that short-chain fatty acids (SCFAs) generated through prebiotic fermentation induce intestinal endocrine cells to secrete glucagon-like peptide-2 (GLP-2), which promotes intestinal epithelial cell proliferation and survival, improving intestinal barrier function [21]. Moreover, beneficial bacteria prevent harmful bacteria from adhering to the intestinal mucosa by competing for adhesion sites and generating antimicrobial substances, thereby minimizing damage to the enteric barrier due to harmful bacteria [22].

5.3. Mechanisms of Synergistic Improvement of Enteric Barrier Function by Dietary Fiber and Prebiotics

The synergistic action of dietary fiber and prebiotics more effectively improves intestinal barrier function. SCFAs produced by dietary fiber fermentation provide energy for beneficial bacteria proliferated under prebiotic action, enabling them to better protect the intestinal barrier . Meanwhile, prebiotics enhance the intestine’s fermentation capacity for dietary fiber after regulating gut microbiota, generating more SCFAs and other beneficial metabolites, which further strengthen intestinal tight junctions, promote mucus secretion, and inhibit harmful bacteria [23]. Their synergy also regulates intestinal immune cell activity, reducing inflammatory damage to the intestinal barrier [24, 25]. For example, SCFAs suppress activity of the nucleus factor-kappa-B (NF-κB) signaling pathway, reducing the production of inflammatory factors like TNF-αand interleukin-6 (IL-6), alleviating intestinal inflammation, and maintaining intestinal barrier integrity [26].

6. SYNERGISTIC IMPACTS OF DIETARY FIBER AND PREBIOTICS IN METABOLIC REGULATION

6.1. Synergistic Action on Blood Glucose Regulation

Dietary fiber and prebiotics exhibit synergistic effects in regulating blood glucose. Soluble dietary fibers such as β-glucan form viscous substances in the bowel, slowing down the digestion of carbohydrates and absorption of glucose, thus lowering postprandial blood glucose peaks [27]. Prebiotics improve insulin sensitivity by regulating gut microbiota. Studies have found that consuming prebiotic-rich foods increases beneficial gut bacteria, which may influence systemic glucose metabolism signaling pathways through metabolites and enhance insulin efficiency. When consumed together, dietary fiber delays glucose absorption, allowing prebiotics more time to regulate gut microbiota and improve insulin sensitivity. Their synergistic action maintains stable blood glucose levels.

6.2. Synergistic Effects on Blood Lipid Regulation

Dietary fiber and prebiotics also synergize in regulating blood lipids. Dietary fiber binds to cholesterol in the intestine, reducing cholesterol absorption and promoting its excretion [28]. Dietary fiber fermentation produces short-chain fatty acids (SCFAs), which suppress the hepatic production of fatty acids and cholesterol. Prebiotics regulate gut microbiota to influence bile acid metabolism: increased beneficial bacteria promote bile acid conversion and excretion while reducing bile acid reabsorption, thereby lowering blood cholesterol levels. Together, dietary fiber reduces cholesterol intake at the intestinal absorption level, while prebiotics promote bile acid metabolism via gut microbiota regulation, achieving lipid-lowering effects through distinct pathways [8]. Studies indicate that the combined supplementation of dietary fiber and prebiotics is more effective in lowering serum total cholesterol and low-density lipoprotein cholesterol levels, elevating high-density lipoprotein cholesterol, and improving lipid profiles.

7. SYNERGISTIC IMPACTS OF DIETARY FIBER AND PREBIOTICS IN IMMUNE REGULATION

7.1. Synergistic Action on Intestinal Immune Regulation

The intestine is a major immune organ, with 70% of immune cells distributed in the gut. Dietary fiber and prebiotics synergize in regulating intestinal immunity. SCFAs produced by dietary fiber fermentation modulate intestinal immune cellular activity, like enhancing macrophage phagocytosis and promoting immunoglobulin A (IgA) secretion [25]. Prebiotics encourage the colonization of beneficial bacteria, which activate intestinal immune cells (e.g., T lymphocytes, B lymphocytes) to enhance the capability of the body to recognize and eliminate pathogens. In synergy, fermentation products from dietary fiber create a favorable immunomodulatory environment for prebiotic-regulated beneficial bacteria, which further enhance dietary fiber’s effects on immune cells. For example, SCFAs promote interactions between beneficial bacteria and intestinal mucosal epithelial cells, activating immune cell signaling pathways and strengthening intestinal immune defense.

7.2. Potential Impacts on Systemic Immune Regulation

The synergistic action of dietary fiber and prebiotics influences not only intestinal immunity but also systemic immunity. The synergistic effect of these components reinforces the intestinal barrier, thereby curbing the infiltration of harmful substances and pathogens into blood and mitigating systemic inflammation [29]. Beneficial metabolites produced by gut microbiota under their joint regulation (e.g., SCFAs) enter the bloodstream and modulate systemic immune cell functions by binding to receptors on immune cells . Studies have found that SCFAs regulate immune cell activity in adipose tissue, liver, and other organs, reducing chronic inflammation and exerting beneficial effects on the immunopathological processes of metabolic diseases like obesity and diabetes [30]. Thus, the synergistic action of dietary fiber and prebiotics may play a vital role in maintaining systemic immune balance and preventing/improving related diseases by regulating gut microecology.

8. CURRENT STATUS AND PROSPECTS

Current research on the synergistic effects of dietary fiber and prebiotics has made progress in mechanisms of gut microbiota regulation, enteric barrier improvement, metabolic regulation, and health promotion via dietary interventions. However, challenges remain, such as unclear optimal synergistic combinations and dose-response relationships for different types of dietary fiber and prebiotics, as well as insufficient understanding of effects and mechanisms across diverse populations (e.g., different ages, health statuses). Future research could focus on: Deepening molecular mechanism studies: Using multi-omics technologies (e.g., metagenomics, metabolomics, proteomics) to comprehensively analyze their impacts on gut microbiota, host cell metabolism, and immunity. Conducting large-scale, long-term human clinical trials: Clarifying optimal application protocols and efficacy evaluations for different dietary fiber-prebiotic combinations across populations. Developing functional foods and supplements: Translating research findings into evidence-based products to improve public health and promote human health. Through such efforts, the mysteries of dietary fiber-prebiotic synergies may be further unraveled, contributing significantly to human health.

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