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From waste to wellness: dietary fiber and polyphenol synergies from plant-based food by-products in gut health and precision nutrition

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ABSTRACT

Vast quantities of by-products generated during plant-based food processing operations represent a rich yet underutilized source of dietary fiber (DF) and bioactive compounds. These offer immense potential for gut health modulation and sustainable resource utilization. This comprehensive review systematically elucidates the classification, advanced extraction technologies, and diverse health-promoting mechanisms of DF derived from these plant-derived processing residues. A central focus of this work is its in-depth examination of the synergistic interactions between DF and polyphenols, uncovering their profound potential in enhancing bioavailability and biological activity—a perspective that contributes to a more comprehensive understanding of their combined impact on health. The review further delineates DF's crucial role in regulating metabolic functions, including glucose homeostasis, lipid metabolism, and intestinal barrier integrity, primarily mediated through gut microbiota-derived short-chain fatty acids and immune-modulatory pathways. This review also explores the application of precision nutrition frameworks to develop individualized fiber interventions. Leveraging host genetics and microbiome variability, it proposes a refined paradigm for future personalized health management. The integration of advanced extraction technologies with detailed mechanistic insights into fiber-polyphenol interactions provides a robust foundation for the development of innovative functional foods and the high-value utilization of these plant-based processing by-products.

1. Introduction

Dietary fiber (DF) refers to the collective term for edible plant-derived components, carbohydrates, and similar substances that cannot be digested or absorbed by the human small intestine but undergo partial or complete fermentation in the large intestine[1]. These include polysaccharides, oligosaccharides, lignin, and related plant materials. Due to their inability to be digested or absorbed by the gastrointestinal tract and hence their inability to provide energy, DF was once considered a "non-nutritive substance" and received little attention for a long time[2]. It was not until the late 20th century that people began to gradually explore the significant health benefits of DF. Based on solubility, DFs are classified into soluble dietary fibers (SDF) and insoluble dietary fibers (IDF). Owing to their distinct physical and chemical properties, play distinct yet complementary roles in the human body. With advancing research, the important role of DF in regulating glucose homeostasis, lipid metabolism, and maintaining intestinal homeostasis has become increasingly evident. Consequently, it has been established as a key functional food ingredient and remains a focal point in current food science research[3].

By-products from agricultural processing typically originate from fruit and vegetable processing, grain and oil processing, livestock and poultry processing, and aquatic product processing[4-7]. Among these agricultural processing by-products, plant-based food by-products are rich in bioactive substances such as vitamins, carotenoids, phenolic compounds, and DF[8], accounting for 20%−30% of the total weight,

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with some exceeding 50%[9]. However, apart from being partially used as animal feed and agricultural fertilizers, most are directly discarded, leading to significant resource waste and environmental pollution[10]. Orange pomace waste contains approximately 47.98% DF by dry matter[11]; grape pomace has 46.17% DF content by dry matter[12]. Rich in DF, these plant-based food by-products represent excellent sources.

The gut serves as the body's most vital organ for nutrient digestion and absorption, as well as its primary immune system, playing a crucial role in maintaining health[13]. With evolving lifestyles and dietary patterns, intestinal diseases have become increasingly prevalent, making gut health an urgent concern. While traditional medications often cause side effects and complications, DF provides an alternative solution that avoids these risks. Recent studies show DF is broken down by gut bacteria into short-chain fatty acid (SCFAs) and other beneficial metabolites, which help suppress inflammatory responses and protect intestinal mucosal barriers, thereby playing a key role in gut wellness[14]. The abundant DF found in plant-based food by-products offers a promising new approach for preventing and treating gut disorders. Additionally, DF acts as a natural carrier for polyphenols, significantly enhancing their bioavailability. The interaction between DF and polyphenols synergistically promotes intestinal health.

This review systematically details DF classification, advanced extraction methods, and diverse functional characteristics from plant-based food by-products. It further elucidates the mechanisms through which these fibers contribute to intestinal health and critically examines their synergistic effects with polyphenols. Crucially, we integrate these insights with the emerging field of precision nutrition, proposing how tailored fiber interventions, informed by individual gut microbiome and genetic profiles, can maximize health benefits. Ultimately, this article aims to establish a theoretical basis for maximizing the value and enhancing the sustainable utilization of plant-based food by-products, offering valuable insights for their practical application in functional food development and personalized nutritional strategies.

2. Classification and extraction methods of DF

2.1 Classification of DF

DF, a carbohydrate polymer with a degree of polymerization of at least 10[15], is often called the "intestinal cleaner" and plays a vital role in gut health. SDF, such as pectin, guar gum, and soluble hemicellulose, are water-soluble and can be fermented by gut microbes. IDF, including insoluble hemicellulose, cellulose, and lignin, are water-insoluble and resistant to fermentation by gut microbes[16].

SDF effectively stabilizes postprandial blood glucose responses, regulates bile acid (BA) metabolism, and can be fermented by gut microbiota to produce SCFAs, thereby helping to maintain the intestinal barrier and overall gut health[17-19]. In contrast, IDF exhibits strong water holding capacity (WHC) and swelling capacities (SC). It increases stool volume and softens its consistency, thereby directly stimulating the intestinal walls and accelerating peristalsis. This significantly shortens the retention time of food residues in the intestines and effectively prevents and alleviates constipation[20]. The synergistic action of both fibers promotes overall health.

The composition of DF plant-based food by-products is different from that of other DF sources. These by-products are more complex in composition, containing abundant polyphenols, which form natural complexes with DF, enhancing their synergistic effects. Compared to other raw materials, fruit peels and residues typically contain richer pectin content and synergize with polyphenols. Citrus peel contained up to 26.9% pectin[21], while apple residue reached 33.3%[22], both being primary commercial sources of pectin[23]. Pectin covalently bound with polyphenols extracted from persimmon waste exhibited excellent emulsifying properties, with this stability influenced by their interactions[24]. Pectin bound to polyphenols from olive residue exhibited strong antioxidant activities and a high antiproliferative capacities *in vitro* against colon carcinoma Caco-2 and leukemia monocytic THP-1 cell lines compared to commercial modified citrus pectin[25]. Wheat bran and corn bran are major sources of arabinoxylan. As core functional components of DF in wheat bran, arabinoxylan exhibited multiple bioactive properties including immune regulation, postprandial blood glucose control, and cholesterol management[26]. Wheat bran and corn bran had DF contents of 48.30% and 65.89%, and arabinoxylan constituting up to 18.6% and 34.06% of the DF, respectively[27]. Compared to traditional DFs, those derived from by-products not only broaden the pathways for high-value resource utilization but also exhibit synergistic effects due to their inherent composite systems, demonstrating significant potential.

2.2 Traditional extraction methods for DF

2.2.1 Enzymatic extraction methods

The enzymatic extraction method utilizes specific enzymes to sequentially remove non-fiber components (primarily proteins, fats, starches, and reducing sugars) from cell matrices. This approach features mild reaction conditions, low energy consumption, and operational simplicity, making it ideal for DF isolation. SDF extracted from *Akebia trifoliata* peel using an enzymatic method achieved a yield of 20.87% under optimal conditions. The obtained SDF not only demonstrated excellent oil holding capacity (OHC), WHC, and SC but also possessed notable *in vitro* antioxidant activity. Furthermore, it effectively inhibited α-glucosidase activity and exhibited strong binding capacities for cholesterol[28]. DF extracted from quince *via* enzymatic method reached a yield of 75.46%. It demonstrated excellent WHC, OHC, adsorption of nitrite ions, as well as the ability to adsorb glucose and cholesterol. Additionally, it exhibited inhibitory activities against α-amylase and lipase, indicating favorable functional properties[29]. Although this method offers mild processing, high efficiency, and low environmental impact, its high cost currently limits large-scale industrial application. The methods for DF extraction are summarized in Table 1.

2.2.2 Chemical extraction methods

The chemical extraction method uses acids or alkalis to extract DF from raw materials. This process separates SDF and IDF *via* centrifugation and alcohol precipitation, while removing impurities (e.g., starch, proteins, fats, pigments), thus enhancing fiber purity and quality. The acid extraction method yielded DF from ginseng residue at a rate of 60.53%, exhibiting enhanced porosity and surface roughness. Compared to enzymatic extraction, DF demonstrates

Table 1
Methods for DF extraction.

No.	Sample	Extraction method	Type	Extraction yield (%)	Physicochemical properties	Biological activity	Publication year	References
1	*A. trifoliata* peel	Enzymatic	SDF	20.87	Excellent WHC, OHC and SC	Notable antioxidant activity, α-glucosidase inhibitory capacity, and cholesterol adsorption capacity.	2024	[28]
2	Quince	Enzymatic	DF	75.46	Excellent WHC and OHC	Effective adsorption of nitrite ions, glucose, and cholesterol; and inhibition of α-amylase and lipase.	2025	[29]
3	Ginseng residue	Acid	DF	60.53	More porous structure, higher apparent viscosity, and significantly enhanced WHC, OHC, and SC	Excellent cholesterol absorption capacity, BA adsorption capacity and glucose adsorption capacity.	2024	[30]
4	Pomegranate peel	Acid	SDF	10.27	WHC, OHC, and SC enhanced	Greater glucose adsorption capacity and antioxidant activity improved.	2020	[31]
		Alkaline	SDF	27.17				
5	Kiwifruit	Acid	IDF, SDF	71.84, 2.78	Favorable OHC and WHC; superior thermal stability (alkali-extracted IDF); looser structure (acid-extracted IDF)	Excellent glucose adsorption, BA binding capacity, and nitrite ion adsorption.	2021	[3]
		Alkaline	IDF, SDF	60.03, 32.85				
6	Potato pulp	Microwave-assisted sodium hexametaphosphate	SDF	44.00	Good SC, as well as moderate WHC, OHC	Excellent cholesterol adsorption capacity and antioxidant activity.	2019	[33]
7	Highland barley bran	Steam explosion-assisted water	SDF	6.96	Decreased thermal stability with increased WHC and OHC	Enhanced cholesterol adsorption, nitrite ion adsorption, and antioxidant capacity.	2023	[34]
8	Papaya	Water combined wet ball milling	DF	35.95	Enhanced viscosity, WHC, OHC, and SC	Enhanced cholesterol adsorption capacity, glucose adsorption, nitrite-ion adsorption capacity and antioxidant capacity.	2024	[35]
9	Quinoa, amaranth, millet	Ultrasound-assisted enzymatic	DF	34.73, 65.51, 66.51	Pore expanding, looser structure and enhanced WHC and OHC	Excellent antioxidant activity.	2018	[36]
10	Grapefruit peel	Microwave-assisted enzymatic	DF	9.13	More complex and loose structure, along with higher molecular weight, improved thermal stability, WHC, and OHC	Enhanced cholesterol adsorption, glucose adsorption, nitrite ion adsorption, and antioxidant capacities.	2020	[37]
11	Highland barley	Extrusion processing and enzymatic	DF	–	Looser, more porous structure and improved WHC and OHC	Blood glucose regulation, cholesterol absorption capacity, nitrite ion absorption capacity, cationic exchange capacity, and antioxidant activity improved.	2025	[38]
12	Ginseng residue	Viscozyme L-wet ball milling	IDF	38.70	Enhanced thermal stability, viscosity, OHC and WHC	BA-adsorption capacity, nitrite ion absorption and nitrite-ion adsorption capacity improved.	2024	[39]
13	Okara	Lactic acid bacteria and *K. marxianus* fermentation	IDF	75.31	Decreased particle size and a looser, more porous structure, along with vanishing edges	Blood glucose-lowering, and lipid-lowering activities were significantly enhanced.	2023	[40]
14	Okara	*M. anka* fermentation	DF	74.20	SDF content, WHC, OHC, and SC improved	–	2020	[41]
15	Navel orange peel	Ultrasound-assisted DES	DF	76.69	Higher SDF content, WHC, OHC, and SC than enzymatic extraction methods	Marked stimulation of *Bifidobacterium* proliferation.	2023	[42]
16	Guava pomace	Ultrasound-assisted DES	SDF	38.24	Increased porosity and enhanced WHC, OHC, and SC	Significantly enhanced glucose and cholesterol adsorption capacities.	2025	[43]
17	Citrus peel powder	PEF-assisted acid	SDF	18.81	Emulsifying properties enhanced	Antioxidant activity improved.	2024	[44]

Note: "–" means not referred.

superior WHC, OHC, cholesterol absorption capacity, BA adsorption capacity and glucose adsorption capacity[30]. The SDF extracted from pomegranate peel using acid and alkaline extraction methods yielded 10.27% and 27.17%, respectively. Compared to the water-extracted SDF, the resulting SDF also demonstrated higher WHC, OHC, and SC, along with considerably greater glucose adsorption capacity and antioxidant activity[31]. Both IDF and SDF extracted from kiwifruit using acid and alkaline extraction methods exhibited excellent OHC, WHC, glucose adsorption capacity, BA binding capacity, and nitrite ion adsorption capacity. The alkali-extracted IDF showed higher thermal stability, while the acid-extracted IDF possessed a looser structure[3]. While chemical extraction is cost-effective, strong acid/alkali treatment may disrupt chemical bonds between DF and associated polyphenols, reducing their bioactivity[32]. Therefore, it is essential to design appropriate extraction processes to preserve its functional characteristics. It also suffers from inconsistent product quality, poor whiteness, and industrial-scale application generates chemical effluents that cause environmental pollution.

2.2.3 Physical extraction methods

Physical extraction method primarily employ physical approaches to extract DF, including hot water extraction, ultrasonication, microwave treatment, and steam explosion, which are predominantly used for SDF extraction. The microwave-assisted sodium hexametaphosphate method achieves a yield of 44% from potato slurry under optimal conditions[33]. The SDF extracted from highland barley bran using steam explosion-assisted water extraction demonstrated a significantly higher content compared to that from non-steam-exploded highland barley bran. Although its thermal stability decreased, enhancements were observed in WHC, OHC, cholesterol adsorption capacity, nitrite ion adsorption capacity, and antioxidant capacity[34]. The extraction yield of papaya DF *via* water combined wet ball milling extraction was 35.95%, which is lower than the 58.85% achieved by the alkaline extraction method. Nevertheless, the resulting DF exhibited superior functional properties, including enhanced hydration characteristics and antioxidant capacity[35]. Despite effectively preserving bioactivity, these methods suffer from low yields, high equipment costs, and significant energy consumption, limiting their industrial-scale application.

Physical extraction method is frequently combined with enzymatic techniques, such as ultrasonic-assisted enzymatic extraction, microwave-assisted enzymatic hydrolysis. Research by Kurek et al.[36] demonstrated that the ultrasonic-assisted enzymatic hydrolysis method achieved significantly higher DF yields from quinoa, amaranth, and millet compared to enzymatic extraction and conventional ultrasonic methods. The SDF extracted from grapefruit peel using microwave-assisted enzymatic method exhibited a more complex and loose structure, higher molecular weight, improved thermal stability, and enhanced WHC, OHC, cholesterol adsorption capacity, glucose adsorption capacity, and nitrite ion adsorption capacity[37]. After being processed by extrusion, the DF extracted from highland barley using enzymatic methods demonstrated significantly improved WHC and OHC. Its functional activities were also enhanced, including blood glucose regulation, cholesterol absorption capacity, nitrite ion absorption capacity, cationic exchange capacity, and antioxidant activity[38]. The yield of IDF extracted from ginseng residue using Viscozyme L-wet ball milling extraction reached 38.7%. Moreover, the resulting IDF demonstrated significantly superior functional properties compared to that extracted by the enzymatic method alone, including enhanced hydration characteristics, BA-adsorption capacity, and nitrite-ion adsorption capacity[39].

Compared with traditional extraction approaches, the combined physical-enzymatic method not only enhances fiber yield but also improves bioactivity, offering advantages in time efficiency, energy conservation, and cost-effectiveness. However, optimizing process parameters to prevent enzymatic deactivation remains a key challenge in advancing this integrated approach.

2.3 Advanced extraction methods for DF

2.3.1 Microbial fermentation methods

Microbial fermentation is an emerging green extraction technology that utilizes the metabolic activity of specific microorganisms or the enzymes they secrete to extract DF. It selectively degrades non-DF components in plant materials through cellulase, hemicellulase, pectinase, amylase, and protease produced during the growth and metabolism of specific microorganisms, thereby achieving DF extraction. Through combined fermentation with lactic acid bacteria and *Kluyveromyces marxianus*, the IDF content of okara increased by 6.80% and reached 75.31%, while processing performance, blood glucose-lowering, and lipid-lowering activities were significantly enhanced[40]. Microbial enzyme systems effectively disrupt the dense crystalline structure and complex cross-linking of IDF, such as cellulose and hemicellulose, partially decomposing them into SDF. This transformation significantly improves product functionality. Deep fermentation of *Monascus anka* with okara yields DF at 74.2%, with SDF content, WHC, OHC, and SC levels showing marked improvements compared to enzymatic methods[41]. Enzymes produced by microorganisms, functioning as biological catalysts, demonstrate high efficiency under mild conditions. This eliminates the need for strong acids or alkalis, thereby reducing chemical residue, environmental pollution, and energy consumption. However, industrial-scale application remains challenging due to complex process design requirements, difficulties in strain screening, and inconsistent product quality.

2.3.2 Deep eutectic solvent (DES) extraction methods

DES are stable solvents formed through intermolecular interactions between hydrogen bond donors and acceptors. By disrupting plant cell walls *via* hydrogen-bond networks, DES enhances DF release with superior extraction efficiency over traditional solvents like water and ethanol. In recent years, DES has been applied as an emerging technology for assisted extraction of DF. DES facilitates lignin separation and enhances DF yield. Ultrasound-assisted DES extraction of navel orange peel yielded DF with significantly higher SDF, WHC, OHC, and SC than enzymatic extraction methods, while markedly stimulating *Bifidobacterium* proliferation to demonstrate prebiotic activity. DES features low melting point, low vapor pressure, biocompatibility, and cost-effectiveness[42]. The ultrasound-assisted DES extraction of IDF from guava pomace yielded 38.24% of a product with increased porosity and significantly enhanced functional properties, including WHC, OHC, SC, and glucose and cholesterol adsorption capacities[43]. The DES method is efficient and environmentally friendly, particularly suitable for developing high-value functional fibers, constituting a breakthrough for sustainable extraction. However, industrial adoption faces challenges including multi-parameter optimization complexity, costly solvent recovery, and scalability constraints. Future integration of DES with green chemistry principles paves the way for transformative food industry applications.

2.3.3 High-voltage pulse electric field (PEF) assisted extraction methods

High-voltage PEF technology is a non-thermal physical extraction method that utilizes transient high-voltage electric fields to disrupt cell membrane structures and promote the release of cellular components, demonstrating unique advantages in efficient DF extraction. Compared with the acid extraction method, PEF-assisted acid extraction of citrus peel powder increased pectin yield by

8.48% and doubled production efficiency (100.23% increase), while the extracted pectin exhibited superior antioxidant and emulsifying properties[44]. PEF effectively preserves the functional activity of DF and is well-suited for industrial-scale applications due to its low energy consumption, high efficiency, yield, and environmental sustainability. However, challenges persist in optimizing complex process parameters and reducing high equipment costs.

3. Investigation on the functional characteristics and mechanisms of DF

3.1 Functional characteristics of DF in metabolic diseases

3.1.1 Combating hyperglycemia and insulin resistance

Frequent, abnormal postprandial glycemic spikes exacerbate insulin resistance and thereby elevate type 2 diabetes risk[45], making blood glucose control crucial for prevention. Conventional hypoglycemic medications often cause side effects like hypoglycemia and gastrointestinal issues, prompting researchers to explore natural products with blood glucose-regulating properties and minimal side effects[46]. DF plays a dual role in blood glucose regulation: it not only helps stabilize postprandial blood glucose fluctuations in the short term but also confers long-term benefits by improving overall metabolic health. DFs obtained from plant-based food by-products have been confirmed to exert functions including blood glucose regulation, as summarized in Table 2.

In the postprandial period, DF modulates blood glucose through 3 direct mechanisms: increasing chyme viscosity to delay gastric emptying, creating a physical barrier within the intestinal lumen to inhibit glucose absorption, and suppressing the activity of digestive enzymes. These combined effects lower the glycemic index of the food, thereby resulting in a blunted postprandial glucose curve with a reduced peak, which effectively prevents sharp glucose fluctuations (Fig. 1). This attenuated glycemic response significantly alleviates the pressure on pancreatic β-cells to rapidly secrete large amounts of insulin, which is crucial for preserving islet function[47]. DF from plant-based food by-products from relatively intact plant cell wall structures. This intact structure preserves its natural three-dimensional architecture and porosity, which provides excellent WHC and SC. These properties increase the volume and viscosity of the chyme, thereby significantly delaying gastric emptying and preventing a sharp rise in blood glucose levels[48].

Table 2
Functional characteristics of DF.

No.	Sample source	Type	Functional properties	Publication year	References
1	Oat bran	DF	Exhibited excellent WHC, glucose-binding capacity, glucose dialysis delay index, and inhibitory activity against *α*-amylase and *α*-glucosidase, which effectively regulated postprandial blood glucose levels.	2024	[50]
2	Corn bran	IDF	Reduced starch digestion rate and controls postprandial blood glucose levels.	2022	[51]
3	Kiwifruit	SDF, IDF	Regulated gut microbiota, promotes intestinal SCFA formation, maintained intestinal homeostasis, and alleviated diabetes in diabetic rats.	2022	[54]
4	Banana peel	DF	Improved gut microbiota dysbiosis, promotes SCFA production, regulates blood glucose, and lowers blood glucose levels in type 2 diabetic mice.	2022	[55]
5	*T. fuciformis* residual substrates	SDF	Enhanced binding capacity toward cholesterol and BAs, effectively ameliorated dyslipidemia and improved lipid metabolism disorders in hyperlipidemic mice.	2023	[59]
6	Wheat bran	IDF	Through the FASN/PPARα and TLR4/MyD88/NF-κB signaling pathways, lowered blood lipids, and prevented obesity.	2025	[60]
7	Okara	DF (fermented by *P. acidilactici* IFJ-1)	Inhibited weight gain in mice fed a high-fat diet, improved blood lipid profiles, reduced hepatic lipid accumulation, and exerted beneficial effects on the gut microbiota and lipid metabolism.	2025	[71]
8	Cassava residue	DF	Adsorbed BAs, enhanced WHC and SC, improved oil-binding and cholate adsorption, thereby contributing to lipid-lowering effects.	2023	[68]
9	Buckwheat	DF	Ameliorated hepatic lipid accumulation and alter the BA profile in mice by activating the gut microbiota-BAs-TGR5/FXR axis.	2025	[69]
11	*U. pinnatifida* fucoidan	SDF	Reduced Bacteroidaceae abundance, increased SCFAs levels, downregulated pro-inflammatory cytokines (TNF-α, IL-6, IL-1β), and ameliorated metabolic inflammation.	2023	[73]
12	Tartary buckwheat bran	SDF	Increased acetate, propionate, and butyrate content in the intestines of *db/db* mice, elevated colonic GPR43 and serum GLP-1 levels, and regulated blood glucose.	2022	[78]
13	Pumpkin			2025	[79]
14	Konjac	SDF	Delayed and inhibited starch digestion, promoted SCFAs production, enhanced GLP-1 expression, suppressed hypothalamic NPY/AgRP, and regulated appetite *via* the gut-brain axis.	2025	[80]
15	Soy residue	SDF	Adsorbed sodium cholate, reduced BA accumulation, accelerated cholesterol metabolism into BAs, thereby lowering cholesterol levels in the body.	2023	[75]
16	Carrot	IDF	Adsorbed bile salts, has good WHC, SC and adsorption capacity of oil and cholate.	2021	[76]
17	Wheat bran	Snailase-modified SDF and IDF	Demonstrated favorable WHC and OHC as well as glucose and cholesterol adsorption capabilities.	2021	[77]
18	Whole wheat flour (fermented by cellulase-producing strains)	SDF	Demonstrated significant cholesterol adsorption capacity and inhibited lipase activity.	2024	[78]
19	Tea seed	DF	Demonstrated strong adsorption characteristics for nitrite ions.	2020	[82]
20	*P. persica* dregs	SDF	Promoted lead excretion, thereby alleviated lead-induced gut microbiota dysbiosis in mice and exerted a protective effect on the mouse intestine.	2023	[84]
21	Soybean dregs	DF (fermented *Trichoderma* spp.)	Modulated gut microbiota in mice, increased intestinal SCFA content, promoted intestinal peristalsis, delayed defecation, and increased fecal output/water content.	2023	[86]
22	Tea leaves	IDF	Combined with water molecules to increase fecal weight/volume, stimulated intestinal walls to induce defecation, accelerated intestinal peristalsis, thereby improving intestinal function.	2022	[87]

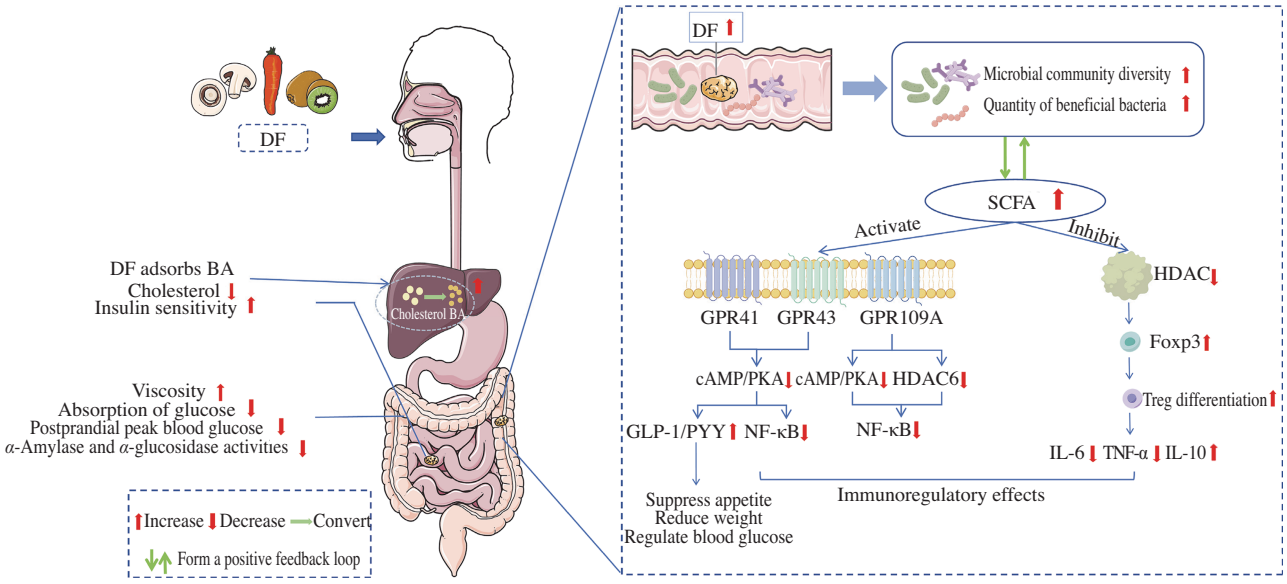

Fig. 1 Cascade effect of DF on blood glucose regulation, gut microbiota modulation, and immune regulation.

As a major source of energy for the human body, starch is hydrolyzed into glucose molecules in the intestine by the enzymes (*α*-amylase and *α*-glucosidase), thereby increasing postprandial blood glucose levels. The porous structure of DF can directly entrap molecules of these digestive enzymes and glucose. This process impedes contact between the enzymes and starch, reducing starch accessibility to the enzymes, which in turn slows the rate of starch breakdown into glucose. Simultaneously, it delays the diffusion of glucose toward the intestinal wall, thereby contributing to the regulation of postprandial blood glucose levels[49]. Oat bran DF exhibited good WHC, which increased food volume and thereby enhanced the feeling of satiety. Additionally, it demonstrated excellent glucose-binding capacity, a high glucose dialysis delay index, and inhibitory activity against *α*-amylase and *α*-glucosidase, which effectively regulated postprandial blood glucose levels[50]. The IDF in corn bran inhibited the activity of *α*-amylase and *α*-glucosidase, significantly reduced starch digestion, and stabilized blood glucose levels[51].

DF also regulates postprandial blood glucose by improving overall metabolic health. Its primary mechanism is acting as a prebiotic, which is fermented and utilized by beneficial gut bacteria such as *Bifidobacterium* and *Lactobacillus*. This process not only promotes the proliferation of these beneficial bacteria while inhibiting harmful ones, thereby enhancing the diversity of the gut microbiota, but also generates SCFAs like acetate, propionate, and butyrate[52]. These SCFAs confer multiple benefits: they help maintain intestinal barrier integrity, reduce chronic inflammation caused by endotoxins entering the bloodstream, and consequently improve insulin sensitivity. This enhancement of insulin sensitivity means the body requires less insulin to effectively transport glucose into cells for utilization, which helps lower fasting and basal blood glucose levels[53]. Furthermore, the acidic environment created by SCFAs further favors the growth of beneficial bacteria, forming a positive feedback loop that continuously optimizes the gut microecology (Fig. 1). SDF and IDF of kiwi fruit can regulate intestinal flora, promote the formation of SCFA in the intestinal tract, and maintain intestinal homeostasis to alleviate diabetes in rats[54]. Banana peel fiber corrected gut dysbiosis, promoting SCFA production through microbial fermentation. These SCFAs stimulated gastrointestinal hormones and insulin secretion for glycemic regulation, lowering blood glucose in type 2 diabetic mice[55].

Polyphenols demonstrate significant potential for preventing and managing type 2 diabetes by exerting multiple mechanisms, including inhibiting intestinal sugar absorption, enhancing insulin sensitivity, and modulating gut microbiota, thereby reducing blood glucose levels and alleviating insulin resistance[56]. However, research on their synergistic effects with DF remains limited, predominantly confined to *in vitro* observations of their inhibitory activity against *α*-amylase and *α*-glucosidase. Whether they can produce synergistic effects *in vivo* and the underlying mechanisms involved represent a critical knowledge gap, warranting further investigation.

3.1.2 Restoring lipid homeostasis and cardiovascular health

3.1.2.1 Cholesterol elimination

Cholesterol is an indispensable functional component of the body's cells, serving not only as a key building block of cell membranes but also participating in vital physiological processes such as steroid hormone synthesis, fat-soluble vitamin metabolism, and BA production. However, elevated cholesterol levels can promote its deposition in the arterial walls, leading to cardiovascular diseases such as atherosclerosis and coronary heart disease. BA provides the key excretory pathway for cholesterol metabolism[57]. DF can bind to BAs, forming complexes that are excreted in feces, thereby interrupting the enterohepatic circulation of BAs and reducing their pool size. Under normal conditions, 95% of BAs are reabsorbed in the distal ileum and recycled by the liver. When DF promotes their excretion, the liver compensates for the depletion of the BA pool by upregulating BA synthesis, which involves increased uptake of low-density lipoprotein cholesterol (LDL-C) from the blood. This results in decreased serum LDL-C levels[58], improved insulin sensitivity, and the establishment of a lipid metabolism regulatory mechanism beneficial to cardiovascular health, ultimately reducing the risk of cardiovascular diseases (Fig. 1). The SDF extracted from *Tremella fuciformis*

residual substrates exhibited significantly enhanced binding capacity toward cholesterol and BAs, effectively ameliorated dyslipidemia and improved lipid metabolism disorders in hyperlipidemic mice[59]. The IDF from wheat bran fermented with *Lactobacillus plantarum* and *Lactobacillus acidophilus* mitigated HFD-induced lipid metabolism disorders through the FASN/PPARα and TLR4/MyD88/NF-κB signaling pathways, lowered blood lipids, and prevented obesity[60]. The role of DF extends far beyond simply increasing BA excretion; its core function lies in profoundly altering the "quality" of BAs through modulation of the gut microbiota. The conversion of primary to secondary BAs is dependent on gut microbiota, which positions DF as a key modulator of this process. Therefore, future research should focus on elucidating how DF "reprograms" the BA profile and, in turn, precisely influences host metabolism.

3.1.2.2 Hepatic lipid reprogramming

The liver serves as the central hub for systemic lipid metabolism, and its dysfunction is a hallmark of various metabolic diseases, including non-alcoholic fatty liver disease. In this process, the "gut-liver axis" plays a critical regulatory role. In recent years, the concept of "hepatic lipid reprogramming" has gained clarity, referring to the systemic reconstruction of the transcriptional and signaling networks that regulate lipid homeostasis in the liver[61]. DF participates in this process by promoting the production of SCFAs and modulating the structure of the gut microbiota.

DF is fermented by colonic microbiota to generate SCFAs, which enter the liver *via* the portal vein. There, they activate the G protein-coupled receptor 43 (GPR43) on hepatocyte membranes and inhibit histone deacetylase (HDAC) activity. This promotes fatty acid oxidation, suppresses the expression of sterol regulatory element-binding protein 1c (SREBP-1c) and cholesterol synthesis-related genes, thereby reducing hepatic lipid accumulation[62]. Additionally, SCFAs stimulate intestinal L-cells to secrete glucagon-like peptide-1 (GLP-1), which inhibits lipogenesis and improves insulin sensitivity, consequently counteracting hyperinsulinemia-driven fat deposition[63-64]. Abnormal lipid metabolism leads to gut microbiota dysbiosis, while DF supplementation reverses this imbalance by promoting the proliferation of beneficial bacteria (such as *Akkermansia* and *Faecalibacterium*) and suppressing harmful bacteria. The resulting altered microbial structure enhances the conversion of primary BAs to secondary BAs, subsequently activating the farnesoid X receptor (FXR) and Takeda G protein-coupled receptor 5 (TGR5) to regulate lipid metabolism. Activation of intestinal FXR induces the secretion of fibroblast growth factor 15/19 (FGF15/19). This factor, upon reaching the liver, not only inhibits hepatic lipogenesis but also downregulates the expression of cholesterol 7*α*-hydroxylase (CYP7A1), preventing excessive BA synthesis and accumulation[65]. Concurrently, TGR5 activation by BAs also promotes GLP-1 release, further contributing to the maintenance of lipid homeostasis[66]. The okara DF after *Pediococcus acidilactici* IFJ-1 fermentation effectively inhibited weight gain in mice fed a high-fat diet, improved blood lipid profiles, reduced hepatic lipid accumulation, and exerted beneficial effects on the gut microbiota and lipid metabolism[67]. Cassava residue fiber significantly reduced serum triglycerides, total cholesterol, hepatic lipids, and hepatic cholesterol while enhancing fecal excretion of lipids and neutral sterols. These effects were comparable to the benchmark cholesterol-lowering drug, simvastatin[68]. Buckwheat DF was found to ameliorate hepatic lipid accumulation and alter the BA profile in mice by activating the gut microbiota-BAs-TGR5/FXR axis, thereby alleviating hyperlipidemia induced by type 2 diabetes[69].

In summary, through its microbial fermentation products (SCFAs) and its regulation of BA metabolism, DF forms a multi-target and multi-level network that profoundly influences the "gut-liver axis" dialogue and actively participates in hepatic lipid reprogramming. Its mechanisms of action span from direct activation of hepatic signaling receptors (GPR43) and epigenetic regulation (HDAC inhibition) to the indirect modulation of systemic hormones (GLP-1, FGF15/19). These effects ultimately converge on four core processes: suppressing lipogenesis, promoting fatty acid oxidation, improving insulin sensitivity, and maintaining BA homeostasis, thereby accomplishing the reprogramming of hepatic lipids.

3.1.2.3 Anti-inflammatory action

Atherosclerosis serves as the primary pathological basis for most cardiovascular diseases, driven by the synergistic interaction of chronic low-grade inflammation and dyslipidemia, which form a self-perpetuating vicious cycle. Under conditions of lipid dysregulation, elevated levels of pro-atherogenic lipoproteins such as oxidized low-density lipoprotein (ox-LDL) and small, dense low-density lipoprotein (sd-LDL) deposit in the subendothelial space. Following oxidative modification, they are engulfed by immune cells like macrophages *via* scavenger receptors, leading to foam cell formation and initiating atherosclerotic plaque development[70]. Furthermore, components such as ox-LDL activate inflammatory signaling pathways in both endothelial and immune cells, exacerbating and sustaining the inflammatory response within the vascular wall. Conversely, a state of inflammation disrupts lipid homeostasis by affecting hepatic lipid synthesis and secretion, as well as interfering with lipid catabolism and storage in peripheral tissues[71]. Within this process, DF demonstrates the potential to interrupt this self-perpetuating vicious cycle. It not only helps maintain lipid metabolic balance but also exerts anti-inflammatory effects through mechanisms such as modulating the gut microbiota and promoting the production of SCFAs. Defatted rice bran-fortified bread was shown to increase the relative abundance of beneficial gut bacteria, such as *Faecalibacterium prausnitzii* and *Bifidobacterium longum*, in healthy adults with low DF intake. This intervention also increased serum high-density lipoprotein cholesterol levels, thereby reducing cardiovascular disease risk[72]. *Undaria pinnatifida* fucoidan modulated the gut microbiota by reducing the relative abundance of Bacteroidaceae and promoting an increase in SCFAs. This mediated its anti-inflammatory properties, leading to reduced levels of tumor necrosis factor-alpha (TNF-α), interleukin-6 (IL-6), and interleukin-1 beta (IL-1β), and ultimately alleviated DF deficiency-induced dyslipidemia and inflammatory responses[73]. In summary, DF provides a multi-target intervention strategy to block the core pathological links of atherosclerosis *via* the "microbiota-metabolism-immune" axis. Its functional properties are manifested not only in traditional lipid regulation but also in shaping a beneficial gut microbiota and promoting the generation of metabolites like SCFAs, thereby exerting systemic anti-inflammatory effects and subsequently preventing the occurrence of various diseases.

3.1.3 Recalibrating energy balance and satiety perception

DF is a key nutritional component in regulating energy balance, capable of reshaping an individual's satiety perception through a series of physiological mechanisms. Due to its high WHC and SC, DF expands in the stomach, increasing the volume and viscosity of chyme, thereby physically distending the gastric cavity and delaying gastric emptying, which leads to prolonged satiety. Furthermore, SCFAs produced by microbial fermentation of DF in the colon activate GPR41/43, reduce cyclic adenosine monophosphate (cAMP) levels and protein kinase A (PKA) activity, and indirectly promote the release of GLP-1 and peptide YY (PYY), thereby suppressing appetite[74]. GLP-1 enhances insulin secretion to improve glycemic control, reduces glucagon release, delays gastric emptying, and decreases food intake by inhibiting appetite-stimulating neuropeptide Y (NPY) neurons in the hindbrain[75-76]. PYY binds to the NPY-Y2 receptor in the arcuate nucleus (ARC) of the hypothalamus, suppressing appetite by inhibiting orexigenic NPY/agouti-related protein (AgRP) neurons while activating anorexigenic pro-opiomelanocortin neurons, playing a critical role in appetite regulation[77]. SDF from buckwheat bran and pumpkin increased colonic acetate/propionate/butyrate, colonic GPR43 expression, and serum GLP-1 in *db/db* mice, improving glycemic control[78-79]. Expandable konjac fiber was shown to delay and inhibit chyme digestion. By promoting the production of SCFAs, enhancing GLP-1 expression, and downregulating hypothalamic NPY/AgRP, it subsequently regulated appetite and digestive processes by stomach-intestine-brain axis[80]. DF modulates energy balance through gastric physical distension combined with microbial fermentation and hormonal signaling. It delays gastric emptying and enhances satiety in the stomach, while also generating SCFAs in the colon that indirectly stimulate the release of GLP-1 and PYY. These effects form an integrated gut-brain pathway for appetite suppression, positioning DF as a key component in functional foods and a promising approach for managing obesity and metabolic diseases.

3.1.4 Elimination of harmful substances and prevention of constipation

DF exhibits excellent adsorption capacity due to its porous structure and large specific surface area. In the intestinal environment, it effectively adsorbs various harmful substances such as nitrite ions and heavy metals. By absorbing water and resisting digestive enzymes, it increases fecal volume and softness, promotes intestinal peristalsis, and thereby prevents constipation. This process not only accelerates the excretion of harmful substances but also significantly shortens their contact time with intestinal epithelial cells, reducing the risk of absorption and related pathological changes[81]. Tea seed DF, with its loose and porous structure, demonstrated strong adsorption characteristics for nitrite ions[82]. In terms of heavy metal removal, DF not only physically adsorbs and retains metal ions but, more importantly, the hydroxyl, carboxyl, and other active groups abundant in its molecules can undergo ion exchange or form stable chelates with heavy metal ions, thereby promoting their excretion *via* feces[83]. SDF extracted from *Prunus persica* dregs effectively promoted lead excretion, thereby alleviating lead-induced gut microbiota dysbiosis in mice and exerting a protective effect on the mouse intestine[84]. Additionally, DF increases fecal volume, directly mechanically stimulating the intestinal mucosa to enhance peristalsis, and the SCFAs produced by its fermentation provide energy for intestinal epithelial cells and promote contraction of colonic smooth muscle, thereby accelerating fecal transit and excretion[85]. Fermented soybean dregs fiber improved WHC, OHC and SC, balanced murine microbiota, elevated SCFAs, reduced defecation interval, and increased stool weight/moisture[86]. Tea leaf IDF increased stool bulk *via* water binding, stimulated bowel movements and accelerated transit[87].

3.2 Mechanisms of DF to maintain intestinal health

3.2.1 Regulation of intestinal flora

The gut microbiota, composed of billions of microorganisms, plays a vital role in gastrointestinal digestion. These microbes metabolize indigestible nutrients, producing SCFAs and bioactive compounds that enhance beneficial digestive processes[88]. DF provides crucial microbial energy, significantly modulating the composition, diversity, and richness of intestinal communities. SCFAs from fiber fermentation regulate intestinal pH, inhibit opportunistic pathogens, and enhance ecosystem stability. The complex and diverse human gut microbiota plays a vital role in maintaining health and ecological balance[89]. Under healthy conditions, the gut microbiota remains stable and resilient, maintaining symbiotic interactions with the host[90]. However, microbial imbalance can lead to compromised intestinal mucosal barriers, weakened immunity, and endogenous infections, potentially causing diseases such as obesity, type 2 diabetes, cardiovascular disorders, and inflammatory bowel disease (IBD)[91-94]. Recent studies have highlighted the regulatory effects of DF from plant-based food by-products on gut microbiota, with multiple findings confirming its ability to maintain microbial balance and mitigate complications caused by dysbiosis. A summary of relevant studies is presented in Table 3. For instance, SDF from sweet potato dregs had been shown to significantly alter the gut microbiota structure in mice. It inhibited the proliferation of harmful bacteria such as *Desulfovibrio*, *Aeromonas*, and *Corynebacterium*, while increased beneficial bacterial populations including *Lactobacillus* and *Faecalibacterium*[95]. The IDF from *Dendrocalamus latiflorus* shoot husks effectively improved gut microbiota diversity and abundance, and promoted a relative increase of beneficial bacteria like *Bacteroides* and *Phascolarctobacterium*. This demonstrated potential advantages in controlling blood glucose elevation, reducing lipid levels, and managing obesity[74]. DF extracted from ponkan peel residue, when modified, can regulate human gut microbiota composition by promoting the growth of beneficial bacteria such as *Megasphaera*, *Prevotella*, and *Collinsella*, while reducing the relative abundance of Bacteroidetes, *Escherichia-Shigella*, and *Enterococcus*[96]. These studies indicate that DF plays a crucial role in regulating intestinal microbiota. In summary, DF derived from various sources can effectively and positively modulate the gut microecology by selectively promoting the proliferation of beneficial bacterial communities, inhibiting the growth of potential pathogens, and enhancing microbial diversity and stability. Their effects are not only beneficial for maintaining the intestinal barrier but also involve key metabolites such as SCFAs, which act as critical signaling molecules mediating systemic physiological effects. Consequently, DF plays a central role in the prevention and management of metabolic and inflammatory diseases.

3.2.2 Restoration of intestinal barrier

IBD is a chronic, recurrent inflammatory intestinal disorder where impaired intestinal barrier function plays a key role in its pathogenesis. The epithelial barrier, the gut's primary defense, prevents translocation of noxious agents (chemicals/pathogens/antigens) while maintaining barrier homeostasis[97]. It effectively blocks harmful substances (including chemicals, pathogens, and antigens) from entering the body. Mucous secretions from goblet cells form a physical protective layer, while tight junctions—transmembrane proteins that bind colon cells—help preserve both intestinal integrity and barrier homeostasis[98]. SCFAs, produced by DF fermentation, enhance epithelial barrier function by regulating antimicrobial peptides secreted by intestinal cells. Butyrate stands out as the most crucial component for maintaining intestinal barrier integrity[97,99]. Recent studies demonstrate that DF can repair intestinal barriers, making it a natural therapeutic agent against IBD, as shown in Table 3. Quinoa bran SDF improved intestinal barrier function by increasing mRNA and protein levels of tight junction proteins, while also enhancing microbial diversity and SCFA production[100]. The SCFAs produced by DF fermentation of lemon powder protected the colonic tight junction barrier and inhibited intestinal inflammatory response[101]. Occludin, a transmembrane protein, participates in maintaining tight junctions within the intestinal epithelial barrier. Grape peel DF attenuated colonic lesion progression, and its IDF increased the expression of Occludin in colonic tissue to repair intestinal barrier function[98]. In summary, DF demonstrates significant potential in intervening in IBD through multiple mechanisms. Its core functions involve enhancing the physical barrier, restoring intercellular connections, and maintaining barrier homeostasis while suppressing inflammation by producing SCFAs, notably butyrate, through fermentation. These findings collectively establish DF as an important natural nutritional strategy for alleviating the pathological process of IBD by repairing the intestinal barrier.

3.2.3 Regulation of intestinal immunity

The gut serves as the body's most vital and complex immune organ, with its immune functions being closely linked to overall health. The extensive mucosal lining in the intestinal tract forms immunomodulatory barrier through its unique architecture, orchestrating both humoral and cellular immunity while maintaining intestinal homeostasist. During microbial fermentation of food, the gut immune system combats and eliminates pathogens such as bacteria, viruses, and harmful food components, thereby protecting the body from damage[102]. DF supplementation enhances immunity and supports gut health. As a vital energy source for the cecal and colonic microbiota, DF enables anaerobic bacteria to activate metabolic pathways under specific intestinal conditions. These bacteria metabolize complex carbohydrates into SCFAs and other metabolites[103]. SCFAs derived from colonic fiber fermentation serve as potent immunomodulators, underpinning fiber's health-promoting effects. SCFAs produced in the gut are partially metabolized locally to maintain homeostasis, while the remainder enters systemic circulation to exert immunomodulatory effects *via* HDAC inhibition or G protein-coupled receptor (GPCR) activation. Specifically, SCFAs activate GPCRs (e.g., GPR41, GPR43, GPR109A) on intestinal epithelial cells and immune cells—including neutrophils, dendritic cells, macrophages, and lymphocytes[104-107]. Activation of GPCRs suppresses the cAMP/PKA signaling pathway, thereby blocking NF-κB signal transduction and attenuating inflammatory responses. Notably, GPR109 activation negatively regulates the NF-κB pathway by inhibiting HDAC6 activity and enhancing inhibitor of nuclear factor kappa B alpha (IκBα) stability (Fig. 1)[108]. Citrus pectin oligosaccharides modulated gut microbiota to enhance SCFA and secretory immunoglobulin A (IgA) production, with downstream augmentation of systemic IgG levels[109]. Fermented soybean residue DF promoted gut microecological stability by regulating gut microbiota composition and metabolite concentrations such as SCFAs and BAs, exerting glucose regulation through the SCFAs-GPR pathway[110]. Lychee pulp fiber complexes promoted SCFA generation and upregulate GPR41/43 expression, while inhibiting the LBP-TLR4-NF-κB pathway to alleviate inflammation-associated constipation[111].

The TLR4/NF-κB pathway serves as the central mechanism underlying chronic inflammatory disorders including obesity, diabetes, and IBD. SCFAs derived from DF fermentation produced through gut microbiota fermentation act as key mediators of its anti-inflammatory effects. These bioactive compounds promote beneficial bacteria like *Bifidobacterium* and *Lactobacillus* growth while inhibiting pathogenic bacterial overgrowth, thereby reducing total intestinal lipopolysaccharide (LPS) levels[112]. As the primary energy source for intestinal epithelial cells, SCFAs stimulate goblet cells to produce mucins, strengthening the physical barrier of the mucus layer and preventing direct contact between bacterial products such as LPS and epithelial cells. Butyrate enhances the expression of tight junction proteins including Occludin and Claudin-1, effectively reducing intestinal permeability and prevents LPS translocation into the bloodstream[113]. Notably, butyrate inhibits the expression of MyD88—a critical signaling molecule in the TLR4 pathway—and suppresses IκB kinase activity. This reduces IκB phosphorylation and degradation, sequestering NF-κB in the cytoplasm where it cannot activate inflammatory gene transcription. Simultaneously, it downregulates TLR4 expression on both intestinal epithelial and immune cell surfaces. SCFAs regulate inflammatory and immune responses by HDAC activity. Upon entering cells, SCFAs directly bind to and suppress intracellular HDACs, thereby upregulating *Foxp3* gene expression. This process promotes the differentiation and development of regulatory T cells (Tregs), enhancing production of the anti-inflammatory cytokine IL-10 while suppressing pro-inflammatory cytokines such as IL-6 and TNF-α (Fig. 1)[114]. Acting as a histone deacetylase inhibitor (HDACi), butyrate increases histone acetylation by blocking HDAC enzymatic activity, upregulates anti-inflammatory gene expression, suppresses pro-inflammatory genes (particularly *TLR4*), and acetylates IκBα to stabilize the IκB-NF-κB complex[115]. Evidence from published studies is summarized in Table 3. American ginseng DF enhanced intestinal immunity in cyclophosphamide-induced immunosuppressive mice by modulating the TLR4/NF-κB pathway, thereby improving clearance of apoptotic cells and abnormal molecules, demonstrating immunomodulatory effects[116]. Wheat-derived arabinoxylan modulated the gut microbiota and promoted butyrate production, which in turn induced the differentiation of colonic regulatory Tregs and suppressed the production of pro-inflammatory factors such as TNF-α, thereby preventing colitis[117].

Table 3
Mechanisms of action of DF in maintaining intestinal health.

No.	Sample source	Type	Functional properties and the mechanisms of action	Publication year	References
1	Sweet potato residue	SDF	Significantly altered gut microbiota structure in mice, inhibited proliferation of harmful bacteria like *Desulfovibrio*, *Aerococcus*, and *Corynebacterium*, and increased abundance of beneficial bacteria like *Lactobacillus* and *Faecalibacterium*.	2021	[95]
2	*D. latiflorus* shoot shell	IDF	Improved gut microbiota diversity and abundance, increased relative abundance of beneficial bacteria like *Bacteroides* and *Phascolarctobacterium*, and regulated blood glucose, lower lipids, and control obesity.	2023	[74]
3	Ponkan peel residue	Complex enzyme modified DF	Modulated human gut microbiota composition, promoted growth of beneficial bacteria like *Megasphaera*, *Prevotella*, and *Collinsella*, and reduced the relative abundance of Bacteroidetes, *Escherichia-Shigella*, and *Enterococcus*.	2023	[96]
4	Quinoa bran	SDF	Increased mRNA and protein expression levels of tight junction proteins, significantly improved intestinal barrier function, and enhanced diversity of gut microbial communities and SCFAs production.	2022	[100]
5	*Citrus limon* peel powder	DF	Produced SCFAs during colonic fermentation, protected the colonic tight junction barrier, and inhibited intestinal inflammatory responses.	2021	[101]
6	Grape peel	DF	Slowed the progression of colonic lesions, increased Occludin expression in colonic tissue, and repaired the intestinal barrier.	2019	[98]
7	Citrus peel	SDF	Modulated gut microbiota, promoted production of SCFAs, sIgA, and IgG, improved immune function.	2019	[109]
8	Soy sauce residue	DF	Promoted gut microecological homeostasis by regulating gut microbiota composition and concentrations of metabolites like SCFAs and BAs, acting through the SCFAs-GPRs pathway.	2024	[110]
9	Lychee pulp	DF	Promoted SCFA production in the gut, significantly enhanced expression of GPR41 and GPR43, and suppressed constipation-related mild inflammation by inhibiting the LBP-TLR4-NF-κB signaling translocation, thereby alleviating constipation in mice.	2023	[111]
10	American ginseng	DF	Enhanced intestinal immunity in cyclophosphamide-induced immunosuppressive mice by regulating the TLR4/NF-κB pathway to increase clearance of apoptotic cells or abnormal molecules.	2023	[116]
11	Wheat-derived arabinoxylan	SDF	Exerted anti-colitis effects *via* a microbiota-dependent mechanism: enhanced butyrate production to promote Treg differentiation and suppress TNF-α.	2023	[117]

After DF is fermented by the gut microbiota to produce SCFAs, it can bidirectionally regulate intestinal and systemic immune functions through 2 core mechanisms: GPCRs signal transduction and HDAC inhibition. Its effects span multiple levels, ranging from strengthening the physical barrier and inhibiting key inflammatory pathways such as TLR4/NF-κB to promoting the differentiation of Tregs, forming a multi-target and systematic immunomodulatory system. These findings establish the solid status of DF as a natural immunomodulator functioning through the gut microbiota-metabolism-immune axis.

4. Synergistic effect and mechanisms of DF and polyphenols

4.1 Synergistic effect of DF and polyphenols

4.1.1 Physicochemical function

Polyphenols can bind to the surfaces and internal pores of DF through either noncovalent or covalent bonding. Polyphenol molecules are rich in phenolic hydroxyl groups, which act as strong hydrophilic groups. These can extensively cross-link with polar groups such as hydroxyl and carboxyl groups on the DF through hydrogen bonds, thereby forming a more dense and stable three-dimensional network. This network effectively traps and retains water molecules through capillary forces and hydrogen bonding, significantly enhancing the WHC and SC of the complex[118]. Furthermore, the aromatic rings of polyphenols confer hydrophobicity. When exposed on the surface of the complex, they increase its overall hydrophobic character, improving the adsorption and binding capacity for lipid molecules through hydrophobic interactions and van der Waals forces, which subsequently improves the OHC of the complex. Concurrently, the physical barrier created by the encapsulation of polyphenols within the DF matrix, along with the bonding effects between them, significantly enhances the thermal stability of both the polyphenols and the resulting polyphenol-DF complex[119]. The SDF from lotus root primarily formed complexes with polyphenols through hydrogen bonding, and these complexes demonstrated significantly superior lipid adsorption capacity and thermal stability compared to lotus root SDF alone[120]. Moreover, the DF from *Rosa roxburghii* tratt pomace exhibited better WHC and OHC than the DF after the removal of bound polyphenols[121]. Non-covalent binding between *Auricularia auricula-judae* SDF and polyphenols resulted in a uniform, smooth lamellar structure, which enhanced the SDF's WHC, OHC, SC, and thermal stability[122]. Similarly, the complexation of steam-exploded-prepared *Lentinus edodes* stalks DF with tea polyphenols improved the thermal stability of the tea polyphenols, and the resulting complexes exhibited significantly greater thermal stability than the DF alone[123]. In summary, the complexes formed between polyphenols and DF through molecular interactions such as hydrogen bonding not only synergistically improve key physicochemical properties of DF including WHC, OHC, and SC but also significantly enhance the thermal stability of the composite system. This synergistic enhancement phenomenon, based on molecular interactions, transcends the functional limitations of individual components and establishes a theoretical foundation for developing novel DF ingredients with superior processing characteristics and physiological functions.

4.1.2 Biological function

DF is fermented by gut microbiota to produce SCFAs, which lower intestinal pH and enhance the overall antioxidative status of the gut, thereby exerting anti-inflammatory effects. Polyphenols exhibit multiple functional activities including anti-inflammatory and antioxidant properties[124]. DF provides both protective and synergistic benefits to polyphenols, enabling them to exert more potent and sustained antioxidant and anti-inflammatory effects—significantly surpassing those achieved by polyphenols alone. DF serves as a natural colon-targeting encapsulation carrier, enabling conjugated polyphenols to reach the colon after digestion in the stomach and small intestine, where they are released under microbial action (Fig. 2)[125]. Upon reaching the colon, polyphenols are transformed by the gut microbiota into various bioactive metabolites. These metabolites, similar to the SCFAs produced from DF fermentation, can inhibit the growth of pathogenic bacteria and promote the proliferation of beneficial probiotics[126]. By working together, they can more effectively improve the structure and diversity of the gut microbiota.

Polyphenols and DF demonstrate marked synergistic effects in anti-inflammatory, antioxidant, and gut microbiota regulation. A key property of polyphenols is their role as potent natural antioxidants, which includes directly scavenging free radicals, inhibiting lipid peroxidation, activating endogenous antioxidant pathways, and suppressing pathogenic bacterial growth[124]. DF functions prebiotically by promoting the proliferation of beneficial bacteria such as *Bifidobacterium* and *Lactobacillus*. The SCFAs produced through microbial fermentation of DF exhibit significant anti-inflammatory activity, alleviating intestinal and systemic inflammation by inhibiting signaling pathways such as NF-κB. Through their synergistic interaction, they enhance the body's overall antioxidant defense capacity and reduce systemic oxidative stress and chronic inflammation levels. Furthermore, polyphenols can inhibit the activity of carbohydrate-digesting enzymes and lipase, thereby reducing the absorption of sugars and fats. Their combined action with DF leads to more effective stabilization of blood glucose, improved insulin sensitivity, and reduced blood lipid levels[127]. Complexes of SDF and polyphenols from lotus root could modulate inflammatory states in high-fat diet-induced mice, prevent liver damage, alleviate hyperlipidemia, and regulate gut microbiota composition. This intervention led to increased Lachnospiraceae and decreased Desulfovibrionaceae/Prevotellaceae in the intestines of high-fat diet-fed mice, thereby promoting gut health[128]. *R. roxburghii* tratt DF-bound phenolics demonstrated superior antioxidant activity, *α*-glucosidase inhibitory activity, and adsorption capacities for nitrite, cholesterol, and BAs compared to its phenol-free counterpart[121]. Complexation of *A. auricula-judae* SDF with polyphenols significantly improved polyphenol retention after *in vitro* simulated gastrointestinal digestion, thereby increasing their bioaccessibility. *In vitro* studies demonstrate that the *A. auricula-judae* SDF-polyphenol complex exhibited potent hypolipidemic activity, suggesting therapeutic potential for hyperlipidemia[122]. Complexation of steam-exploded shiitake stem DF with tea polyphenols significantly enhanced steam-exploded shiitake stem DF's adsorption capacity for fatty acids, cholesterol, and BAs[123]. In summary, combining DF with polyphenols enhances the bioavailability of polyphenols while improving both their physicochemical properties and biological activity. The interaction between DF and bound phenolic compounds facilitates their joint participation in intestinal fermentation. This synergy not only boosts their bioavailability but also amplifies DF's positive regulatory effects on gut health.

4.2 Mechanisms of action of DF-polyphenol complex in colon-targeted delivery

DF is typically resistant to degradation by gastric acid, pepsin, and small intestinal digestive enzymes. It forms DF-polyphenol complexes through physical encapsulation, hydrogen bonding, hydrophobic interactions, van der Waals forces, or covalent bonds with polyphenols. During the gastric digestion phase, the acidic

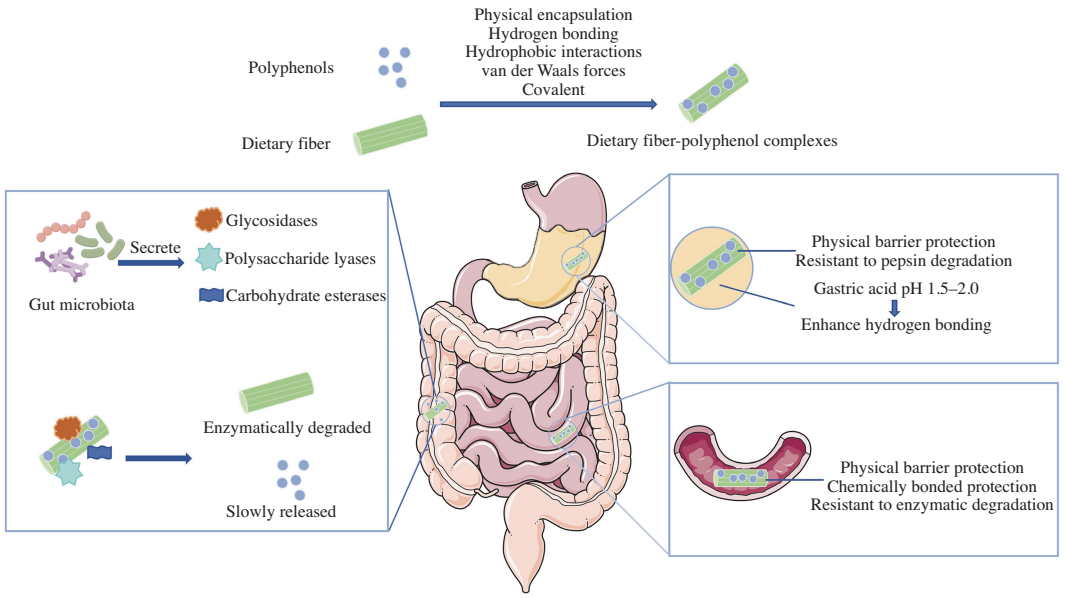

Fig. 2 Colon-targeted delivery and release mechanism of DF-polyphenol complex.

environment of gastric juice strengthens the hydrogen bonding between polyphenols and DF. Since DF is not broken down by pepsin, it provides a physical barrier for polyphenols. In the small intestinal digestion phase, DF resists degradation by enzymes, offering both physical protection and protection through chemical binding for polyphenols. This mechanism reduces premature release and absorption of polyphenols in the stomach and small intestine, allowing them to reach the colon intact or primarily as complexes, thereby enabling targeted colonic delivery of polyphenols (Fig. 2). The colon hosts a diverse microbial community that produces carbohydrate-active enzymes such as glycosidases, polysaccharide lyases, and carbohydrate esterases, which break down DF[123,129]. This process allows slowly released polyphenols bound to DF in the colon. Polyphenols then synergize with beneficial metabolites like SCFAs produced during DF fermentation to collectively maintain gut health. Phenolic compounds bound to IDF from triticale released minimal amounts during gastrointestinal digestion, while partially releasing them gradually through colonic fermentation under intestinal microbiota influence as IDF structure breaks down. These phenolic compounds worked with DF to modulate microbial community structure and function, promoting SCFAs production in the colon[130]. Compared to adzuki bean seed coat DF supplemented with polyphenols, IDF-bound phenolic compounds from red bean seed coats more effectively reduced histopathological damage in mouse colon tissues, decreased serum inflammatory mediators and colonic oxidative stress levels, regulated tight junction protein expression, and maintained the integrity of the colonic epithelial cell barrier. By inhibiting the TLR4/NF-κB inflammatory signaling pathway, it alleviated inflammation in ulcerative colitis mice while increasing beneficial gut bacteria abundance and reducing harmful bacterial levels, thereby counteracting DSS-induced intestinal dysfunction in colitis models[131]. Angosteen peel DF-bound phenols not only effectively lower the pH value of fermentation broth during processing but also significantly promote SCFAs production. This adjustment reduced the Firmicutes/Bacteroidetes ratio in gut microbiota, positively regulating microbial composition and enhancing metabolic activity. Compared with self-assembled mangosteen peel DF-bound phenol mixtures, the assembled formulation released significantly fewer phenolic compounds and total phenols during simulated gastrointestinal digestion. This indicated that a higher proportion of bound phenolic compounds coexist with DF in the colonic fermentation process[132]. DF provides a comprehensive colonic-targeted delivery system for polyphenols, offering both stability protection in the upper digestive tract and precision release in the lower digestive tract mediated by microbial metabolism. This sophisticated process, characterized by temporal and spatial specificity, not only maximizes the preservation of polyphenol bioactivity but also enables multidimensional synergism at the colonic site. Through coordinated interactions with DF metabolites and gut microbiota, the system facilitates multifaceted intestinal protective functions.

5. DF and precision nutrition

Mounting evidence indicates that variations in nutrient requirements and metabolic responses stem from genetic makeup, physiological characteristics, lifestyle, and environmental exposures, necessitating personalized nutrition solutions—termed precision nutrition—to optimize health and prevent disease[133-134]. Technological advances provide robust frameworks for implementing precision nutrition, where multi-omics integration and AI-driven analytics serve as foundational pillars. Cutting-edge omics technologies (genomics, transcriptomics, metabolomics) have elucidated molecular crosstalk among genes, gut microbiota, and nutrients. The convergence of AI algorithms and big data has spawned intelligent tools—wearables, sensors, mobile/web applications—that optimize dietary planning, digital dietary logging, nutrient-targeted recommendations, and health monitoring. Through analysis of user-generated self-tracking data, these systems generate personalized recommendations[135]. Such AI solutions play a pivotal role in advancing precision nutrition practices.

As previously mentioned, DF plays a crucial role in regulating blood glucose, lowering blood lipids, reducing body weight, modulating gut microbiota, and maintaining intestinal health. Gut microbiota serves as a key characteristic of precision nutrition, with significant individual differences in how people respond to DF. A core determinant of these responses lies in gut microbiota composition. Precision nutrition emphasizes viewing humans as super-symbiotic entities when selecting foods or implementing nutritional interventions, optimizing health through personalized nutritional support while preventing, managing, and treating diseases[136]. Human gut microbiota can be stratified into enterotype-like community configurations, most prominently *Bacteroides*-dominated and *Prevotella*-dominated types, while a *Ruminococcus*-dominated type has been reported but less consistently detected across Asian populations[137-138]. These enterotype-like patterns closely reflect long-term dietary habits: *Bacteroides*-dominated communities exhibit stronger protein/fat breakdown capabilities, responding well to high-protein diets but showing weaker fermentation capacity for high-fiber diets. High-dose fiber supplementation may lead to bloating and other intolerance symptoms. *Prevotella*-dominated communities are rich in polysaccharide-degrading enzyme systems, enabling efficient fermentation of complex carbohydrates. Studies demonstrate that individuals with *Prevotella*-dominated communities show significantly higher SCFAs production after consuming whole grain fiber compared to *Bacteroides*-dominated counterparts.

Precision nutrition strategies should be tailored to microbial profiles by adjusting fiber types and dosages—for *Prevotella*-dominated communities, recommend complex carbohydrates (e.g., whole grains, legumes), while for *Bacteroides*-dominated communities, gradually increase fermentable fiber intake to avoid acute gastrointestinal reactions[139]. Beyond microbial differences, host genetic polymorphisms significantly influence DF metabolism. Studies reveal that the rs10485463 polymorphism in free fatty acid receptor 2 affects SCFAs signaling pathways: individuals carrying the T allele exhibit reduced butyrate sensitivity, requiring higher fiber doses to achieve equivalent metabolic improvements. APOE ε4 carriers demonstrate superior cholesterol-lowering effects from *β*-glucan supplementation compared to non-carriers, while individuals with phosphatidylethanolamine-*N*-methyltransferase gene mutations show more pronounced responses to DF in improving fatty liver[140-141].

Despite its promising prospects, precision nutrition still faces multiple challenges in promoting DF. The lack of unified microbial profiling standards and detection protocols, combined with significant individual variations in gut microbiota influenced by antibiotics, makes targeted interventions difficult. Public misconceptions about

DF persist, such as the common belief that "coarser texture equals higher fiber content" or the misguided pursuit of excessive fiber intake causing gastrointestinal discomfort, highlighting the need to enhance public health literacy. As a key carrier of precision nutrition, DF's health benefits have expanded from traditional constipation relief to multidimensional applications including reversal of cancer-associated metabolic disorders and homeostatic maintenance. With deep integration of microbiome and nutrigenomics, precision nutrition based on DF is poised to become a crucial preventive measure, offering cost-effective solutions for chronic disease prevention and management.

6. Conclusion and prospect

This comprehensive systematically elaborates on the significant potential of plant-based food by-products as a sustainable source of DF. These fibers demonstrate notable efficacy in key physiological pathways, including glycemic and lipid homeostasis, detoxification of heavy metals, with particularly prominent roles in modulating gut microbiota and immune function. However, a significant knowledge gap remains regarding the synergistic effects between DF and polyphenols in human physiological mechanisms. Future research should employ cutting-edge multi-omics technologies to systematically decipher the complex "host-microbiota-diet" interaction network and focus on individual variability to advance the development of personalized nutrition strategies. Integrating advanced extraction technologies with mechanistic research will ultimately guide the transformation of the agricultural food system towards a more circular and health-promoting model.

Declaration of competing interests

The authors declare that they do not have any conflict of interest.

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