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Extensive inhibition and mechanisms of starch digestion by dietary fiber: A comprehensive review

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ABSTRACT: The rapid digestion of starch is closely linked to an elevated risk of diet-related chronic conditions. In recent years, blending starch with other food components has become a common strategy to slow its digestibility. Among various approaches, dietary fiber (DF) has drawn considerable interest owing to its marked inhibitory effects on starch digestion. Although numerous studies have reported these effects, systematic discussions of the underlying mechanisms remain scarce. In this review, we first classified the factors that influence the impact of DF on starch digestion and examined the interrelationships among them. We then systematically dissected the inhibitory mechanisms, which included direct interactions between DF and starch that altered starch physicochemical properties, suppression of digestive enzyme activity, increased viscosity or altered mass transfer, and modulation of gut microbiota and their metabolites. In addition, we surveyed the applications of DF-mediated regulation of starch digestion in the food industry, where consumer demand and acceptance for such functional products were steadily growing. This review thus offers important insights for the development of slow-digesting foods.

Keywords: Dietary fiber; Starch digestion; Interaction; Enzyme activity; Gut microbiota; Physical barriers

1. Introduction

Rapid economic growth has driven a marked shift toward highly refined modern diets, contributing to a rising prevalence of obesity, hyperlipidemia, and diabetes. These conditions have emerged as a significant global issue that poses a serious threat to public health ¹. The rising incidence of metabolic diseases has garnered increased attention toward the research on starch digestion, which is the primary carbohydrate affecting blood sugar levels ². At the same time, non-communicable diseases have now come to dominate the global disease burden, accounting for more than 70% of all deaths worldwide ³.

Starch serves as a primary energy source for humans. Once ingested, it is hydrolyzed by digestive enzymes into glucose, supplying 45% to 65% of daily energy requirements ³⁻⁵. Recent investigations revealed a strong correlation between starch digestion and various chronic illnesses ⁶. Postprandial blood glucose responses depend on the type, quantity, and digestive behavior of the starch consumed. Starches with slow digestion properties help maintain glycemic balance by attenuating postprandial insulin release and improving insulin sensitivity ⁷. Currently, the digestive properties of starch are influenced by several

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factors. The first is the origin and type of starch itself, which encompasses granule architecture, crystalline pattern, particle size, and molecular structure⁸. Second, non-starch components in starch-based food formulations, such as proteins, lipids, polyphenols, and dietary fibers (DF), and their interactions with starch, also affect the physical and structural properties of the food system⁹. Additionally, the processing and modification of starch are equally significant, including thermal treatment, extrusion treatment, and chemical modification¹⁰. Notably, DF within the food matrix stands out as particularly influential.

DF is a type of non-starch polysaccharide that remains undigested and unabsorbed, providing significant health benefits⁷. In food systems, DF frequently co-exists with starch and is often added as a functional ingredient to improve the physical, chemical, and nutritional properties of food products. Research indicated that increased DF consumption is associated with reduced starch digestion and a lower glycemic response¹¹⁻¹². When starch and DF are present together in food, their interaction can markedly affect the physicochemical and nutritional properties of both components¹³. For example, the addition of pectin to starchy foods can increase system viscosity, which in turn slowed starch digestion and absorption, leading to a more gradual and controlled rise in blood glucose¹⁴. Furthermore, DF may interact with starch to form complexes that are resistant to digestive enzymes, thereby limiting the availability of starch for absorption¹⁵. Such mechanisms may contribute to lower calorie intake and improved gut health¹⁶. However, despite the growing body of research, the precise mechanisms underlying the interaction between DF and starch during food processing and within the human gastrointestinal system, along with their impact on the inhibition of starch digestion, remain insufficiently understood. Further research is therefore needed to clarify these processes and to better harness the health benefits of slowly digestible foods.

The review summarized and generalized existing studies to elucidate the factors affecting DF on the inhibition of starch digestion, and it analyzes the interconnections among these factors. It further outlined the regulatory mechanisms through which DF suppressed starch digestion and discussed the applications of DF–starch interactions in the food industry. Building on current findings, we proposed strategies to advance the development of slowly digestible starch-based products, with the aim of strengthening the theoretical basis for formulating low glycemic index (GI) starchy foods and offering novel product development approaches for the prevention and management of chronic diseases.

2. Overview of starch and its digestion property

2.1 Starch

Starch is a complex polysaccharide composed of amylose and amylopectin. Amylose is a linear polymer linked by α -1,4 glycosidic bonds, primarily found in the amorphous regions of starch. In contrast, amylopectin is a highly branched molecule formed by both α -1,4 and α -1,6 glycosidic bonds, predominantly located in the crystalline regions of starch⁴. From a structural hierarchy perspective, starch can be classified into multiple scales, including molecular structure, crystal structure, growth rings, lamellar structure, and granular structure. These structural features significantly influence the gelatinization, rheological, and digestion properties of starch¹⁷⁻¹⁸. Notably, the nutritional value of starch is contingent upon its form and

quantity of intake. Inadequate consumption may lead to health issues such as obesity, diabetes, cardiovascular diseases, and abnormal blood sugar levels. For these reasons, precisely modulating starch digestibility within food systems is of considerable importance, particularly for populations at risk of such metabolic disorders.

The types of starch vary, which in turn affects their digestion properties. Starch can be classified into three categories based on its digestibility: rapidly digestible starch (RDS), slowly digestible starch (SDS), and resistant starch (RS). Among these, RDS is rapidly digested and absorbed in the small intestine within 20 min, leading to a sudden increase in blood sugar concentration, which is detrimental to health. In contrast, SDS undergoes gradual hydrolysis over a period of 20 to 120 min. Due to its dense internal structure, SDS exhibits strong resistance to digestive enzymes, allowing for a slow decomposition process that provides a continuous and stable energy supply while avoiding sharp fluctuations in blood sugar levels. Conversely, RS escapes digestion entirely in the small intestine; it passes to the colon where it undergoes microbial fermentation, contributing to satiety while yielding little caloric value⁵. Accumulating evidence suggested that, provided total energy intake is adequate, foods with a lower proportion of RDS and higher contents of SDS and RS are more favorable for health. Such products are particularly suited as functional foods for individuals with diabetes, gastrointestinal disorders, or those aiming to control body weight¹⁹⁻²⁰.

2.2 The digestion process of starch

The digestion of starch is a continuous process that begins in the mouth and extends throughout the entire gastrointestinal tract. During digestion, starch is gradually hydrolyzed into glucose through the action of various enzymes (salivary amylase, pancreatic amylase, and pepsin), leading to an increase in blood sugar levels. The undigested portion, however, enters the colon to participate in microbial fermentation. Subsequently, RS is fermented by specific colonic anaerobes, resulting in the production of short-chain fatty acids (SCFAs) and other significant metabolic products that contribute to the enhancement of the gut microecological system²¹. **Figure 1** systematically illustrated the digestive environment of each organ in the human digestive system, along with the related enzymes and their specific roles in starch decomposition.

The digestive process commences in the oral cavity, where salivary α -amylase initiates the hydrolysis of ingested starch. However, due to the brief residence time of food in the mouth, this digestive action is relatively limited. Chewing, the primary mechanical digestive activity in the oral cavity, creates favorable conditions for subsequent digestive processes in the gastrointestinal tract. Upon entering the stomach, the acidic environment facilitates the conversion of pepsinogen into pepsin, which primarily targets the protein constituents in starch. Notably, despite the pH changes within the stomach, salivary amylase retains a certain level of activity and continues to participate in the enzymatic hydrolysis of starch, which is significant for subsequent digestion in the small intestine⁶. The small intestine is the principal site of starch digestion. Here, pancreatic amylase efficiently hydrolyses the α -1,4 glycosidic bonds of starch, producing intermediates such as maltose. These breakdown products must then be further digested into glucose by enzymes like maltase and glucoamylase, which are secreted by the epithelial cells lining the small intestinal

villi, before they can be absorbed and utilized by the body ¹⁸. The undigested starch components, particularly RS, ultimately reach the large intestine. In the absence of digestive enzymes in the large intestine, these residual starches are primarily fermented and utilized by intestinal microorganisms, generating SCFAs that offer various health benefits, including reducing inflammatory responses, lowering the risk of colon cancer, and enhancing intestinal barrier function ²². The digestion of starch predominantly relies on α -amylase, released by saliva and the pancreas, to break it down into maltose, isomaltose, and short-chain dextrin. These products are then further digested into monosaccharides by glycosidases on the brush border of the small intestine for absorption. However, the presence of DF can significantly inhibit this digestive process through multiple mechanisms.

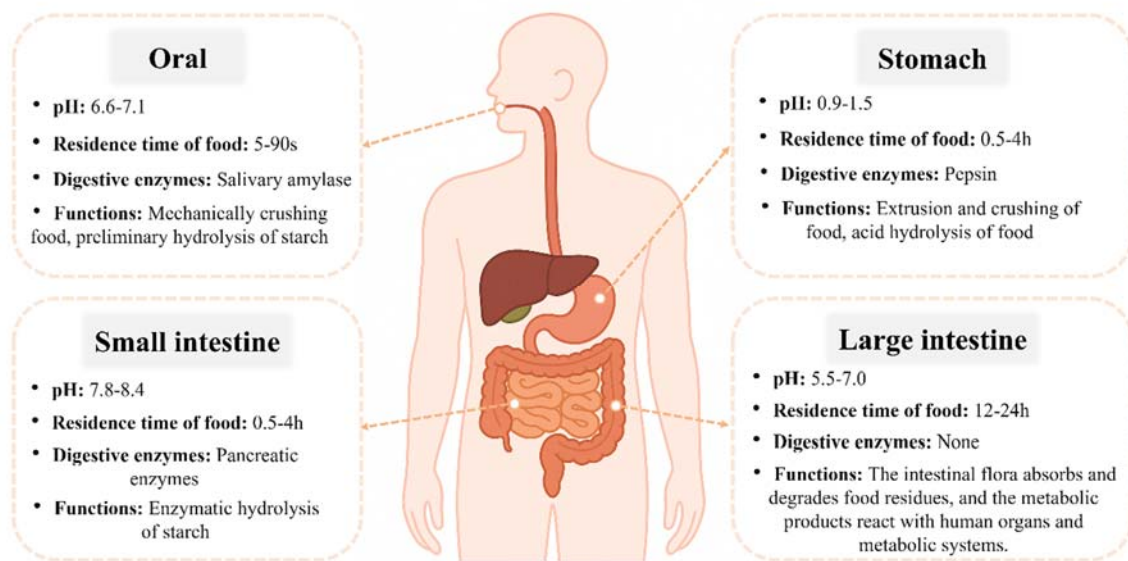


Figure 1 Digestive processes of starch and related environments

2.3 Static *in vitro* digestion method

The static *in vitro* digestion model, due to its operational simplicity and cost-effectiveness, has emerged as the predominant approach for *in vitro* digestion studies today. This model can be categorized into two fundamental types based on experimental requirements: the single-compartment system, which simulates only one digestion phase (either the gastric or intestinal phase), and the multi-compartment system, which encompasses multi-phase digestion involving the oral cavity, stomach, and small intestine. During the experiment, the simulation parameters for each digestion phase including the secretion rate of digestive fluids, pH, and bioactive substance concentrations, are kept constant at preset values ²³. This fixed-parameter experimental approach is unable to replicate the gastrointestinal peristalsis, chyme mixing, and pH gradient variations observed in actual digestion. Consequently, static models are primarily suitable for the initial validation of digestion conditions and for the rapid assessment of experimental materials.

In 1992, researchers developed an improved method to determine the digestion of starch in food systems including rice and cornflakes. The procedure first included incubating the masticated samples with pepsin at an acidic pH and 37 °C, followed by a reaction with amylase for 21 h ²⁴. Research has shown that results obtained with this method are in good agreement with *in vivo* data. It should be noted, however, that

varying the model parameters can markedly affect the outcomes of the static digestion model²⁵⁻²⁶. To improve the comparability of trials, the globally acknowledged standard static *in vitro* digestion model (INFOGEST) has methodically standardized essential parameters and created an *in vitro* simulation system appropriate for adult food digestion. Since its release in 2014, this model has been widely applied *in vitro* digestion studies of food and was upgraded to the more advanced INFOGEST 2.0 version in 2019²⁷⁻²⁸. This standardized model divided the digestion process into three stages. The first stage is the preparation stage: determination of enzyme activity and bile; preparation of simulated salivary fluid (SSF), simulated gastric fluid (SGF), and simulated intestinal fluid (SIF), and pH testing. The second stage is the digestion stage. 1. Oral stage: food and SSF are mixed at a ratio of 1:1, CaCl₂ and salivary amylase are added, and the mixture is incubated at 37 °C and pH 7 for 2 min. 2. Gastric stage: the oral chyme and SGF are mixed at a ratio of 1:1, pepsin and gastric lipase are added, and the mixture is incubated at 37 °C and pH 3 for 2 h. 3. Intestinal stage: the gastric chyme and SIF are mixed at a ratio of 1:1, bile and pancreatic enzymes are added, and the mixture is incubated at 37 °C and pH 7 for 2 h. The final stage is the sampling stage, where samples are taken from different digestion stages based on the specific experimental purpose²⁸.

The INFOGEST static digestion model has been instrumental in studies investigating how DF inhibits starch digestion, offering a standardized platform to quantitatively assess their effects on starch hydrolysis. Liu et al.²⁹ applied this model to show that Soluble DF (SDF) from sweet potato, modified with alkaline hydrogen peroxide, was markedly more effective than its unmodified counterpart at suppressing starch hydrolysis and reducing glucose diffusion rates. They further demonstrated that SDF from sweet potato, owing to its higher viscosity and stronger gel-forming properties, restricted the access of digestive enzymes to starch substrates by elevating chyme viscosity, thereby hindering starch breakdown. Beyond this, other researchers have used the INFOGEST static digestion model to explore how DF influences starch digestion kinetics. Viscous SDF like xanthan gum, guar gum, and locust bean gum, for instance, exerted only modest effects on starch digestion at low viscosity, but at higher concentrations they substantially lowered both starch digestibility and glucose release. Among these, xanthan gum maintained the highest viscosity throughout the simulated gastrointestinal passage and proved most effective at curbing glucose diffusion³⁰. In a separate study, Ahmed et al.³¹ employed the INFOGEST model to reveal that intact pea cell walls can effectively entrap starch granules, limiting enzyme infiltration and diffusion, which in turn reduced the starch digestion *in vitro*.

2.4 Dynamic *in vitro* digestion model

In contrast to static models, dynamic models exhibit greater complexity and more accurately reflect the digestive process. Dynamic digestion models simulate at least one dynamic characteristic of the gastrointestinal tract, primarily focusing on the gastric stage, and replicate dynamic processes such as fluctuations in the pH of chyme and the regulated secretion of enzymes. Currently, most research on dynamic models emphasizes the simulation of dynamic changes in gastric juice pH and mechanical studies, including gastric peristalsis and shear force²³. The pH of gastric juice and gastric motility significantly

influence protein hydrolysis, particularly the modulation of pepsin activity. Variations in gastric juice pH affect the conformation and structure of proteins, thereby impacting protein hydrolysis and the digestion of other conventional nutrients^{23,32}.

To overcome the limitations of INFOGEST static digestion models, researchers have in recent years developed a range of dynamic *in vitro* digestion systems that better mimic physiological events such as gastric emptying, pH gradients, gastrointestinal peristalsis, and continuous secretion of digestive juices. These models provide a more faithful recreation of how DF exert their inhibitory effects during the actual digestive process³². For example, work using the DIVRSD dynamic rat gastroduodenal model showed that pectin can form highly viscous gel networks that entrap starch granules, markedly delaying gastric emptying and slowing starch hydrolysis. Microstructural observations confirmed that the pectin-containing chyme exhibited higher dynamic viscosity and storage modulus, with starch granules physically trapped within the gel matrix, thereby restricting enzyme accessibility and penetration³³. Similarly, the gastrointestinal model, a multi-compartment dynamic system, allowed sequential sampling from the stomach, duodenum, jejunum, and ileum. Studies have revealed that the suppression of starch hydrolysis by DF was not a simple static endpoint effect but rather a dynamic process that varied across intestinal segments; the thickening effect of DF was most pronounced in the gastric phase and gradually diminished as the digesta moved into the small intestine and became diluted by secreted fluids³⁴.

It is worth noting that predictions from dynamic models can diverge considerably from those obtained with static setups. In one comparative study, for instance, the inhibitory effect of cinnamon on starch hydrolysis in rice pudding was only detectable with the dynamic model, while the INFOGEST static model failed to capture it, likely because the dynamic system more closely approximated real physiology by integrating gastric acid secretion, emptying kinetics, and peristaltic mixing³². Taken together, dynamic digestion models, by accounting for gastric emptying dynamics, pH shifts, and intestinal motility, offer a more physiologically relevant platform than static models for investigating the mechanisms by which DF inhibit starch digestion.

2.5 *In vivo* digestion evaluation

In terms of *in vivo* evaluation, the modulation of starch digestion by DF is typically assessed through postprandial glycemic responses. The GI introduced by Jenkins et al.³⁵ in 1981 has been widely used to characterize the glycemic impact of different foods. Essentially, it is determined by measuring the area under the blood glucose response curve after ingestion of a carbohydrate-containing food, thereby reflecting the rate of starch digestion and glucose absorption. In addition, Wolever et al.³⁶ pointed out in 1991 that insulin response can serve as an indicator of the body's ability to regulate glycemic fluctuations. More recently, researchers have incorporated parameters such as gastric emptying rate and incretin hormone levels to provide a more comprehensive evaluation of the effects of DF on starch digestion and metabolic health³⁷. Under *in vivo* conditions, the modulation of starch digestion by DF spans the entire gastrointestinal process of digestion and absorption, and the underlying mechanisms have been validated in numerous animal and

human studies. In the gastric phase, highly viscous SDF such as pectin and β -glucan significantly delay gastric emptying, thereby reducing the rate at which chyme enters the small intestine³⁸. Ellis et al.³⁹ observed *in vivo* that the addition of guar gum markedly increased the viscosity of small intestinal contents, while concurrently decreasing the rate of glucose absorption, indicating that the viscosity effect is a key mechanism in suppressing starch digestion. Furthermore, intact plant cell walls or insoluble DF can restrict starch accessibility through physical entrapment. He et al.⁴⁰ demonstrated in human trials that the unbroken cellular structures in whole grains significantly reduce starch digestibility and postprandial glycemic responses.

3. Factors affecting the inhibition of starch digestion by DF

3.1 The inherent properties of DF

3.1.1 Types

Numerous DF derived from cereals, fruits, vegetables, and edible fungi have been shown to effectively impede starch digestion. From the perspective of solubility, these DF are categorized into soluble, insoluble, and semi-soluble types. SDF primarily consists of components such as pectin, β -glucan, and inulin, which readily dissolve in water. Insoluble DF (IDF) are the main constituents of the cell walls of grains and nuts, and they are also the most abundant components in the bran of grains, including cellulose, hemicellulose, and lignin. Research indicated that SDF exhibited greater viscosity than IDF and may more efficiently reduce the *in vitro* hydrolysis rate of starch⁴¹.

A number of studies have shown that, within an appropriate concentration range, the inhibitory effect of DF on starch digestion becomes more pronounced as the dose increases⁴²⁻⁴³. Conversely, some research indicated that excessive DF may diminish this inhibitory effect⁴⁴⁻⁴⁵. Furthermore, comparative analyses have highlighted distinctions among various types of DF. Among the four SDF studied, carboxymethyl cellulose, high methoxy pectin, guar gum, and xanthan gum, the digestion of rice starch decreased with increasing concentrations of carboxymethyl cellulose, high methoxy pectin, and guar gum, while no significant dependence was observed with xanthan gum content. Notably, all four SDFs significantly reduced the contents of RDS and SDS, while increasing RS levels¹². It was noted that the IDF from kiwifruit was more effective in inhibiting α -amylase activity compared to its SDF counterpart. Interestingly, kinetic analysis revealed that the SDF from kiwifruit acted as a non-competitive inhibitor, whereas the IDF functioned as a mixed-type inhibitor, exhibiting both non-competitive and competitive characteristics⁴⁶. In the wheat starch system, both SDF and IDF were found to reduce the proportion of RDS while increasing the proportion of SDS⁴⁷. Even at a low addition level of 0.1%, DF from both highland barley and quinoa significantly altered the gelatinization characteristics of rice starch and enhanced RS content. Among these, the SDF from quinoa was particularly effective in inhibiting gel network formation⁴³. Regarding cellulose types, the incorporation of hemicellulose resulted in the most pronounced reduction in noodle digestibility, followed by lignin and cellulose⁴⁸. Overall, DF demonstrates a broad inhibitory effect on starch digestion; however, variations exist among different types of DF.

3.1.2 Structure

The inhibitory effect of DF on the starch digestion process is intricately linked to its structural characteristics, encompassing key parameters such as monomer composition, chain length, branching degree, and functional group distribution. These structural attributes directly influence the solubility, viscosity, and adsorption capacity of DF. Consequently, they play a pivotal role in modulating the efficiency of its interactions with starch and digestive enzymes. For instance, β -glucan, a type of DF found in oats, possessed a primary chain composed of β -1,3/1,4-glucose, which enabled it to form a high-viscosity solution that encapsulated starch granules. Research indicated that oatmeal rich in β -glucan can significantly diminish starch hydrolysis⁴⁹. However, the simple-structured cellulose with β -1,4-glucose, without branches, had a significantly weaker inhibitory effect due to its lack of viscosity⁵⁰. The impact of molecular weight is also considerable. Corn bran cellulose with low molecular weight can penetrate the starch structure, and its embedding effect on starch was limited. In contrast, corn bran cellulose with high molecular weight possessed a complex spatial structure that allowed it to completely encapsulate the starch particles, hence more effectively preventing enzymes from interacting with the starch. The inhibitory effect of high molecular weight cellulose was significantly much superior than that of its low molecular weight equivalent⁵¹. Similarly, the research by Guo et al. further confirmed that the molecular weight and solution concentration of oat β -glucan were positively correlated with its effect of delaying starch digestion, which was manifested in a decrease of the GI and an increase of SDS and RS content⁴⁵. Chang et al. demonstrated that molecular weight variations of feruloylated oligosaccharides from rice bran alter their aggregation behavior, consequently modulating their inhibitory capacity against rice starch digestion. Notably, low-molecular-weight showed the strongest inhibitory activity, owing to their distinctive loose and fragmented conformation⁵².

The functional group of DF can be further enhanced through chemical modification. Nsor-Atindena et al. previously discovered that nano-sized cellulose exhibited a more potent inhibitory effect on amylase compared to micro-sized cellulose⁵³. Numerous researchers have made significant efforts to improve the physicochemical characteristics of cellulose. For instance, carboxymethylation treatment can incorporate highly polar carboxymethyl groups into the cellulose structure, effectively increasing its polarity. The negative charges introduced through this process can generate electrostatic repulsion with amylase. Experimental findings indicated that incorporating 0.28% carboxymethylated cellulose suppressed α -amylase and glucoamylase activities by 28% and 20%, respectively, representing a considerable improvement over the inhibition achieved with unmodified cellulose⁵⁴. The inhibitory effect of chitin nanofibrils on starch hydrolysis was highly dependent on size, surface charge and concentration. The most effective inhibition was observed at a high concentration of 4%⁵⁵. The research findings clearly demonstrated that by meticulously regulating the structural characteristics of DF, it is possible to effectively optimize its capacity for starch encapsulation, enzyme inhibition effects, and complex formation properties. This optimization facilitated precise control over the starch digestion process.

3.2 Pre-treatment of DF

In the contemporary food processing industry, characterized by the continuous emergence of novel technologies, various pretreatment processes, including enzymatic hydrolysis, thermal denaturation, and ultrasonic treatment, are employed to modify DF. As shown in **Table 1**, these pretreatments can effectively enhance the inhibitory effect of DF on starch digestion. Such pretreatments can significantly alter the structural properties of DF, which in turn influence its capacity to regulate starch digestibility.

3.2.1 Physical treatment

Certain processing and pretreatment methods can markedly affect the inhibitory characteristics of DF on starch digestion. Among these methods, physical field-based treatments are the most widely used, effective, and practical. Since they do not involve chemical reagents, these approaches are safe, environmentally friendly, and cost-effective. Techniques such as ultrafine grinding, high-pressure homogenization, extrusion, microwave treatment, and cold plasma application can disrupt the cell wall structure of DF, thereby increasing their specific surface area. This increase facilitates a physical interaction with starch, ultimately enhancing the barrier effect against amylase activity.

Physical processing effectively alters the structural characteristics of DF through different mechanisms of action, consequently influencing its interaction and digestion behavior with starch. Microwave treatment generated thermal and non-thermal effects through the rapid rotation of polar molecules in an electromagnetic field, which can effectively disrupt the crystalline regions of DF⁵⁶. Chen et al. discovered that microwave treatment effectively reduced the molecular weight of oat β -glucan while simultaneously enhancing its water-holding capacity. When this modified DF was combined with starch, it significantly slowed the *in vitro* digestion rate of starch and ultimately diminished the overall extent of digestion⁵⁷. The localized high temperatures generated by microwaves can disrupt hydrogen bonds within fiber molecules, thereby exposing additional hydroxyl groups and enhancing interactions with starch molecules. This process led to the formation of a physical barrier that hindered enzyme contact. Conversely, ultrasonic treatment primarily altered the fiber structure through mechanical forces and free radicals produced by the cavitation effect⁵⁸. Li et al. reported that ultrasonic treatment increased the solubility of corn bran-derived DF while reducing its viscosity. Following gelatinization with corn starch, this modified DF significantly decreased the RDS fraction⁵⁹. This modification was attributed to the depolymerization of DF molecules induced by ultrasonic treatment, which increased their ability to complex with amylose and resulted in a more compact network topology. Extrusion treatment represents a comprehensive physical modification method that simultaneously applies high temperature, high pressure, and high shear force. The process leads to the formation of a porous structure on the surface of DF particles, thereby improving their capacity to adsorb amylase and promoting the formation of DF-starch complexes⁶⁰.

3.2.2 Chemical modification

Chemical modification technology has garnered extensive attention in recent years due to its considerable advantages. DF molecules possess a high density of alcohol hydroxyl groups, which primarily

interact with chemical reagents, resulting in the synthesis of diverse modified cellulose types. Chemical methods typically involve hydrolyzing, oxidizing, or cross-linking DF using strong acids or bases. These treatments can modify the solubility and distribution of functional groups within DF, resulting in irreversible changes to its molecular structure and thereby improving its ability to inhibit starch digestion⁶¹⁻⁶². Research findings indicated that konjac glucomannan, when treated with 0.24% Na₂CO₃ and 0.5% NaHCO₃, underwent a transformation into a fibrous state. This fibrous alteration significantly enhanced its adsorption capacity for amylase, thereby inhibiting the hydrolysis of starch⁶³. The insoluble cellulose derived from alkali-treated rice bran and wheat bran contained a minor quantity of hemicellulose and lignin. This composition facilitated the cross-linking of fibrillar cellulose, resulting in a more porous fiber network structure and an increased specific surface area of cellulose, which exposed a greater number of active hydroxyl groups. Consequently, this enhanced structure exhibited a stronger adsorption capacity for glucose, fatty acids, and cholesterol. Additionally, its semi-crystalline architecture imparts greater resistance to digestion in the fibers⁶⁴. Nonetheless, it is important to acknowledge that chemical modification approaches encounter considerable obstacles in applications. On one hand, numerous chemical reagents react with alcohol hydroxyl groups, which can affect the contact sensitivity of DF with enzymes and may persist in the final product, thereby posing potential health risks. On the other hand, the modification process may generate environmental pollutants. Consequently, the use of chemical reagents in the food industry remains highly controversial. Future research should focus on developing safer and more environmentally friendly green chemical modification processes.

3.2.3 Enzyme modification

Enzyme modification technology has garnered significant attention in recent years due to its environmentally friendly and efficient characteristics. The selective decomposition of specific constituents within DF using enzymes such as cellulase and xylanase may reduce viscosity and enhance the accessibility of active sites. This process facilitates for precise regulation of the molecular structure of DF, thereby optimizing its influence on starch digestion. Corn bran SDF modified by xylanase and cellulase demonstrated reduced molecular weight. These smaller molecular fragments can more readily penetrate the interior of starch particles more readily and interact with starch molecules through hydrogen bonds, effectively hindering the action of digestive enzymes^{59, 65}. The surface of the co-modified IDF, obtained through ball milling and cellulase treatment, exhibited a wrinkled appearance and a sparse pore structure. In comparison to the original IDF, the water-holding capacity, oil-holding capacity, and swelling capacity of the co-modified IDF increased by 38.5%, 22.2%, and 25.0%, respectively. Furthermore, this structural modification significantly enhanced various functional properties, including glucose adsorption, inhibition of glucose diffusion, interference with starch gelatinization, and suppression of digestive enzyme activity. This improvement was ascribed to the porosity architecture established by cellulase treatment, which enabled the co-modified IDF to develop an efficient network topology⁶⁶. Future research should focus on the precise control of the enzymatic hydrolysis process to achieve targeted regulation of molecular weight

distribution. Additionally, the synergistic amalgamation of many enzymes may substantially augment their inhibitory effects on starch digestion. These findings will provide essential theoretical basis for the development of a new generation of starch digestion regulators.

Table 1 Effect of DF pretreatment on the inhibition of DF on starch digestion

Pre-processing methods	Implementation methods	DF types	Starch types	Effects on the digestive property of starch	References
Deacetylation and high-pressure homogenization	Nano-chitin was treated in 30% NaOH solution at 90 °C for 4 h, followed by 4 cycles of high-pressure homogenization at 500 bar.	Nano-chitin	Corn starch	The nano-chitin treated with deacetylation and high-pressure homogenization was most effective in reducing starch digestion and delaying glucose release. Starch hydrolysis rate and glucose diffusion were reduced from 89% and 583 μmol to 66% and 386 μmol , respectively.	⁵⁵
Embedding and high-pressure homogenization	1g nano-chitin was stirred for 30 min, then NaClO was added, followed by 4 cycles of high-pressure homogenization at 500 bars.	Nano-chitin	Corn starch	The nano-chitin treated with embedding and high-pressure homogenization showed stronger inhibition of gastric protein digestion from 358 μmol to 129 μmol .	⁵⁵
Dynamic high-pressure microfluidization	Pretreatment at 50, 100, 150 and 200 MPa.	DF from bamboo shoots	Rice starch	DF incorporation significantly reduced the GI value. Under 100 MPa, the RDS content was reduced by about 37%, and the RS content was about twice that of natural starch.	¹¹
Homogenization	7 cycles at 100 MPa were processed through a microfluidizer.	IDF and Nanofibrillated cellulose from rice bran, wheat bran, and carrageenan	Potato starch	Both IDF and Nanofibrillated cellulose delayed glucose release, with NFC exhibiting superior digestion resistance.	⁶⁴
Extrusion process	Extrusion temperature, screw speed, feed rate and water addition were 160 °C, 210 rpm, 16 kg/h and 29%, respectively.	IDF from corn gluten	Corn starch	There was a significant decrease in RDS content, degree of starch hydrolysis, and glyco-isomerization index of starch.	^{51, 65}
Extrusion puffing	The extrusion temperatures were set at 90 °C, 110 °C and 80 °C, the screw speed was 40 rpm and the end diameter was 10 mm.	DF from bamboo shoots	Rice starch	DF-starch aggregates inhibited enzyme accessibility to starch.	⁴⁴
Steam blasting	1.18 MPa pressure and 92 s residence time.	DF from Ginkgo stem	Wheat starch	Wheat starch hydrolysis (60.9 $\pm$ 0.90%) and glycemic index (84.10 $\pm$ 4.39) were reduced to 43.01 $\pm$ 0.78% and	⁶⁷

Damp treatment	heat	Steam at 100 °C for 2 minutes and 10 min.	DF from psyllium	Wheat starch	68.45±3.15 with the addition of 12% DF from ginkgo stems. RS content increased from 9.0% to 18.2% at 10 min of steaming.	68
Dry treatment	heat	Baking on hot plate at 100 °C and 250 °C for 2 min.	DF from psyllium	Wheat starch	There was no significant change in RS content under baking at 100 °C, which decreased from 23.5% to 20.6% under baking at 250 °C.	68
Fermentation		Under the conditions of 10% inoculum, pH 5.8, and fermentation time of 41 hours, the fermentation of green wood mold using.	SDF from rice bran	Potato starch	The addition of SDF retarded the pasting of starch in the dough and reduced the GI value of the cookies, 73.69% to 62.47%.	69
Fermentation		<i>Trichoderma viride</i> was utilized to ferment on a reciprocal shaker under the conditions of inoculum size 10%, pH 5.8, and 41 h.	SDF from rice bran	Wheat starch	The GI value of starch with 10.8% of fermented SDF added was significantly reduced.	69
Acid hydrolysis		Hydrolysis of β -glucan in 1% hydrochloric acid at pH 1.0 for 5 hours and 10 h.	β -glucan from <i>Hericium Erinaceus</i>	Wheat starch	The starch gel without acid hydrolysis contained the high level of SDS and RS and the low GI value of 59.33%.	70
Acid hydrolysis		Extraction in citric acid solution with pH 3.5 for 30 min at 80 °C.	DF from <i>Tamarindus</i> seeds	Corn starch	DF increased the apparent viscosity of starch and was retarding starch viscosity decay.	71
Acid hydrolysis		Extracted in citric acid solution with pH 5.5 at 55 °C for 1.5 h.	DF from wheat bran	Corn starch	4 times volume DF added to the starch, the digested starch content was reduced from 61.53% to 50.48%. And it had obvious inhibitory effect on α -amylase.	42
Acid hydrolysis		Extracted in 72% sulfuric acid solution for 1 h at 30°C.	SDF from rice bran	Rice starch	Starch hydrolysis was reduced by the addition of 3%, 6% and 9% SDF from rice bran.	48
Acid hydrolysis		Ultrasonic treatment with 85% phosphoric acid at 45 °C for 1 h.	Corn gluten cellulose	Wheat starch	Phosphoric acid modification improved the inhibitory effect of treated cellulose on starch digestion, as evidenced by a stronger glucose diffusion inhibition, reduced inhibition of amylase activity, and RS enhancement.	50

3.3 Food processing procedures and food systems

Most of the starch consumed undergoes various forms of processing. The processing within the food system plays a crucial role in the inhibition of starch digestion by DF. Thermal treatment, mechanical shearing, extrusion, and fermentation can markedly alter the physicochemical properties of DF, thereby modulating its inhibitory capacity. These processing methods may induce dissolution, degradation, cross-linking, or structural reorganization of DF matrix, which in turn affect its water-holding capacity, viscosity, adsorption behavior, and interactions with starch. Research has shown that careful manipulation of processing conditions may maximize the functional characteristics of DF, thereby improving its efficacy in delaying starch hydrolysis.

Heat treatment methods like as steaming, baking, blanching, and thermal extrusion may facilitate the degradation of some IDF at elevated temperatures. This technique transforms them into SDF, markedly improving their viscosity and water retention capability. Steaming is a commonly used thermal treatment method that largely alters the structure of DF by the introduction of humid heat. The solubility of β -glucan in oats enhanced post-steaming, enabling the formation of a viscous gel matrix within the digestive system. This gel network may efficiently encapsulate starch granules, creating a physical barrier that reduces α -amylase accessibility⁷². The dry heat treatment during baking can induce Maillard reaction and caramelization reaction in DF. During the baking process, starch underwent gelatinization, enhancing its digestibility. Li et al. showed that baking whole wheat flour at 180 °C for 20 min induced partial cross-linking of arabinoxylan, forming a more stable network structure⁶⁵. Furthermore, psyllium DF has been shown to inhibit the formation of amylose-lipid complexes while simultaneously increasing the viscosity of gelatinized starch. This produces a more robust paste that establishes a physical barrier, so obstructing amylase's access to starch granules⁷³. Similarly, twin-screw extrusion can increase the specific surface area of bamboo shoot DF, form a porous structure on the surface, and reduce the hydrolysis index of rice starch⁴⁴. In contrast, fine processing removed the fiber-rich parts such as the bran of grains, leading to a significant reduction in DF content. This treatment destroyed the natural protective barrier of starch, making it easier for digestive enzymes to break down the starch and thus accelerating the digestion rate⁷⁴.

In addition, fermentation, as a biological processing method, substantially modifies DF through the metabolic activities of microorganisms such as lactic acid bacteria and yeast. During the fermentation process, certain polysaccharides in DF are decomposed to generate SCFAs and oligosaccharides. These metabolites not only help maintain gut microbial balance but can also indirectly influence starch metabolic efficiency. In whole wheat bread production, for instance, pre-fermentation partially degrades DF while simultaneously increasing the SDF fraction. This alteration subsequently altered starch digestion kinetics, resulting in a slower release rate⁷⁵⁻⁷⁶. The inoculation of yeast, *Lactobacillus plantarum*, *Lactobacillus rhamnosus* and *Bacillus coagulans* promoted the transformation or degradation of the DF from rye, with a notable degradation observed in fructan⁷⁶. Consequently, various processing methods significantly affect the digestion process of starch by modifying the physicochemical properties of DF.

In the real food system, DF frequently engages with diverse components via active groups to form intricate systems, which subsequently influence the digestibility of starch. Research has demonstrated that psyllium DF can effectively inhibit the formation of starch-glycerol monostearate complexes; however, the addition of glycerol monostearate does not significantly alter the inhibitory effect of DF on starch digestion⁷³. This interaction was component-dependent. Tannic acid can interfere with the intermolecular interaction between polysaccharides and starch, thereby weakening the inhibitory effect of konjac glucomannan and κ -carrageenan on starch hydrolysis⁷⁷. It is worth noting that the synergistic effect of pectin and flavanols can markedly decrease the hydrolysis rate of starch, as well as RDS content and GI value, while increasing RS content. This synergistic effect exhibited a concentration-dependent relationship. At low concentrations, pectin diminished the inhibitory action of flavanols on α -glucosidase, which was attributed to its non-covalent interactions with both the enzyme and flavanols. Conversely, at high concentrations, pectin formed a binary complex with α -glucosidase, leading to an inverse trend⁷⁸. Similarly, the inhibitory effect of pectin combined with mulberry polyphenols or rutin on α -amylase was stronger than that of the single components, which was attributed to the synergistic effect of polyphenols and the gel network structure of pectin⁷⁹. These findings revealed the complex regulatory mechanism of molecular interactions in food multi-component systems on the digestion behavior of starch.

3.4 The connections among different affecting factors

Collectively, the studies discussed above indicate that the mechanisms by which DF slows starch digestion are governed by multiple interrelated factors that interact in a complex manner to modulate the digestive process. **Figure 2** schematically illustrated the relationships among these various influencing factors. Under various processing methods, changes in structure and properties enhances the interaction between DF and starch, thereby improving the inhibitory effect on starch digestion. Ultimately, the ability and potential of DF to inhibit starch digestion and reduce postprandial glycemic responses have been confirmed in various real food systems.

Firstly, the inhibitory effect of DF on starch digestion is fundamentally shaped by its type and structure. DF derived from different sources possesses distinct chemical compositions and physical properties, resulting in varying mechanisms of interference with starch digestive enzymes. SDF tends to impede enzyme-substrate interactions by creating a high-viscosity environment⁴¹, whereas IDF primarily restricts the solubilization and enzymatic hydrolysis of starch through physical barrier effects⁷¹. It is worth noting that the structural characteristics of DF, including molecular weight and degree of branching, further influence its interaction with starch⁵¹. Long-chain DF are more prone to forming enzyme-resistant complexes with starch through hydrogen bonding, while highly branched DF may hinder enzyme binding through steric hindrance¹³.

Furthermore, the pretreatment methods applied to DF can significantly modify its physicochemical properties, thereby influencing its effectiveness in inhibiting starch digestion. By disrupting the cell wall structure of the DF, a greater number of active groups become available for interaction with starch; however,

this process may also lead to a reduction in viscosity due to a decrease in particle size⁸⁰. Fermentation treatment can degrade non-starch polysaccharides in DF through microbial action, leading to the generation of SCFAs and other metabolic byproducts. This process indirectly regulates the gut microenvironment and slows down starch digestion⁸¹. Proper processing can effectively optimize the physicochemical properties of DF, thereby enhancing its functional performance in food systems. Studies have shown that DF from wheat bran subjected to airflow micronization exhibited significantly reduced particle size, a more concentrated particle size distribution, and increased specific surface area, which enhanced its interaction with starch, showing a notable thickening effect, promoting starch gelatinization while inhibiting its digestion *in vitro*⁷⁴. Similarly, steam explosion treatment increased the content of SDF in apple pomace and produced finer molecular structures. When used in bread making, it not only improved the textural properties of the final product but also enhanced its sensory acceptance⁸². The efficacy of various pretreatment approaches is often correlated with the original structure of the DF. Dense cellulose structures necessitated high-intensity treatments to release their inhibitory potential, whereas excessive treatment may compromise the gel properties of pectin.

Food processing systems further modulate the interaction between DF and starch. Heat treatment is one of the most commonly used unit operations in food processing, including baking, steaming, and frying thermal processing techniques. Heat treatment can facilitate the formation of DF-starch complexes, but prolonged exposure to high temperatures may also damage the active groups within DF. Notably, there is a dynamic relationship between processing conditions and DF types. β -glucan may increase viscosity with modest heat treatment; however, excessive heating may result in molecular breakdown⁸³. A study on hawthorn seed polysaccharides and wheat starch showed that co-thermal treatment enabled them to interact through weak hydrogen bonds and strong electrostatic forces, forming a complex with an ordered double-helix structure. This interaction further induced the crystalline configuration of wheat starch to change from A-type to V-type, and V-type crystals were usually closely associated with lower digestibility⁸⁴. These processing parameters may also indirectly amplify the inhibitory effect of DF by altering the degree of starch gelatinization.

In conclusion, the inhibitory effect of DF on starch digestion arises from the synergistic interplay of its type and structure, pretreatment processes, and food processing systems. The three elements demonstrate a hierarchical connection, with the structural qualities of DF serving as the primary predictor of its attributes. The intrinsic properties of DF dictate its functional potential and guide the selection of appropriate pretreatment methods. Furthermore, pretreatment techniques modulate its performance activity, while processing conditions ultimately influence its efficacy within complex food matrices. Future research should prioritize the analysis of multi-factor interactions to accurately design DF-starch composite systems with specific slow-digestion functionalities, thereby providing valuable insights for practical applications.

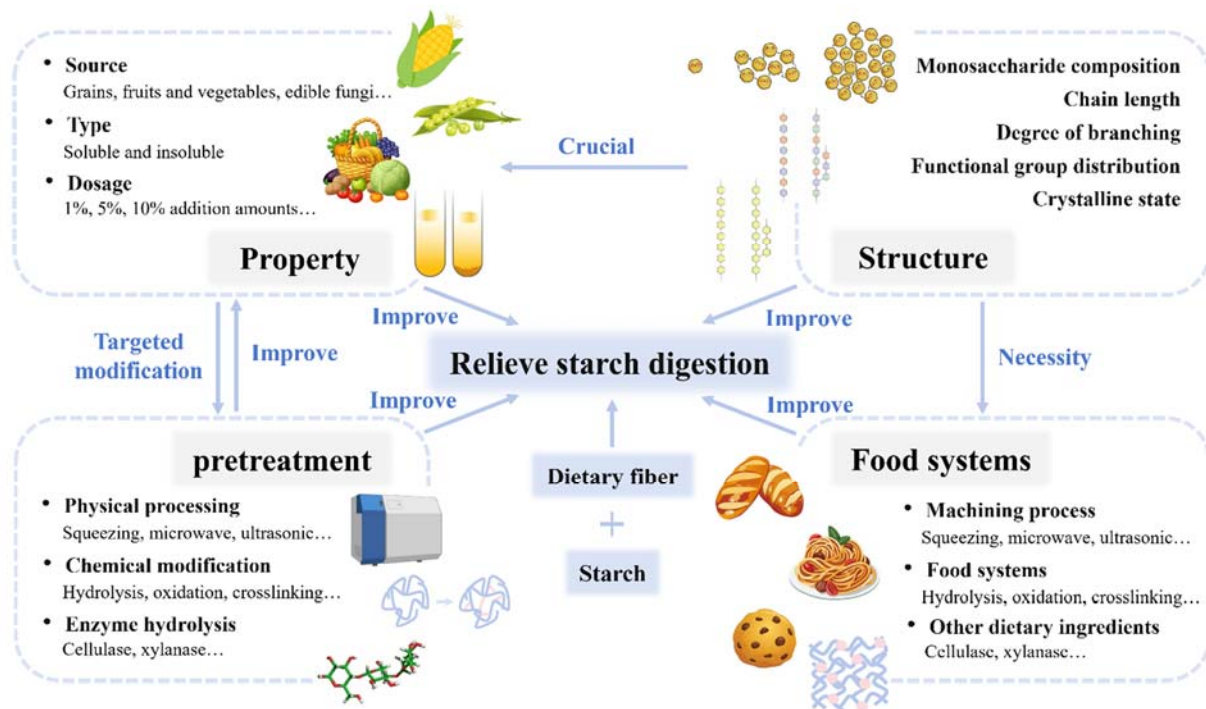


Figure 2 Relationships between the inhibition of starch digestion by DF and various influencing factors

4. The possible mechanism on the inhibition of DF on starch digestion

A large number of studies have shown that DF has a certain impact on the digestion of starch, but there is no consistent conclusion on the mechanism by which the presence of DF affects the digestion of starch. Current investigations mainly focus on SDF. It has been found that SDF diminished starch digestion by modifying the microstructure of food or by inhibiting the interaction between starch and water due to the dissolution and hydration of non-starch polysaccharides, thereby restricting starch gelatinization. Overall, DF can modulate the digestion property of starch through various mechanisms. This regulatory effect is most evident in the following aspects, shown in **Figure 3**. First, DF interact directly with starch, altering its crystallinity and gelatinization behavior, or physically encapsulate starch granules, thereby enhancing resistance to enzymatic breakdown and favoring the formation of RS. DF may also coat digestive enzymes or bind to their active sites, limiting the accessibility of starch to hydrolysis, which is reflected in reduced in vitro digestibility. In addition, certain SDF markedly elevate the viscosity of the chyme, slow gastric emptying, and promote a greater sense of satiety. Finally, DF modulates gut microbiota along with its metabolites. Certain gut microbiota and their metabolites can influence metabolic efficiency regarding starch.

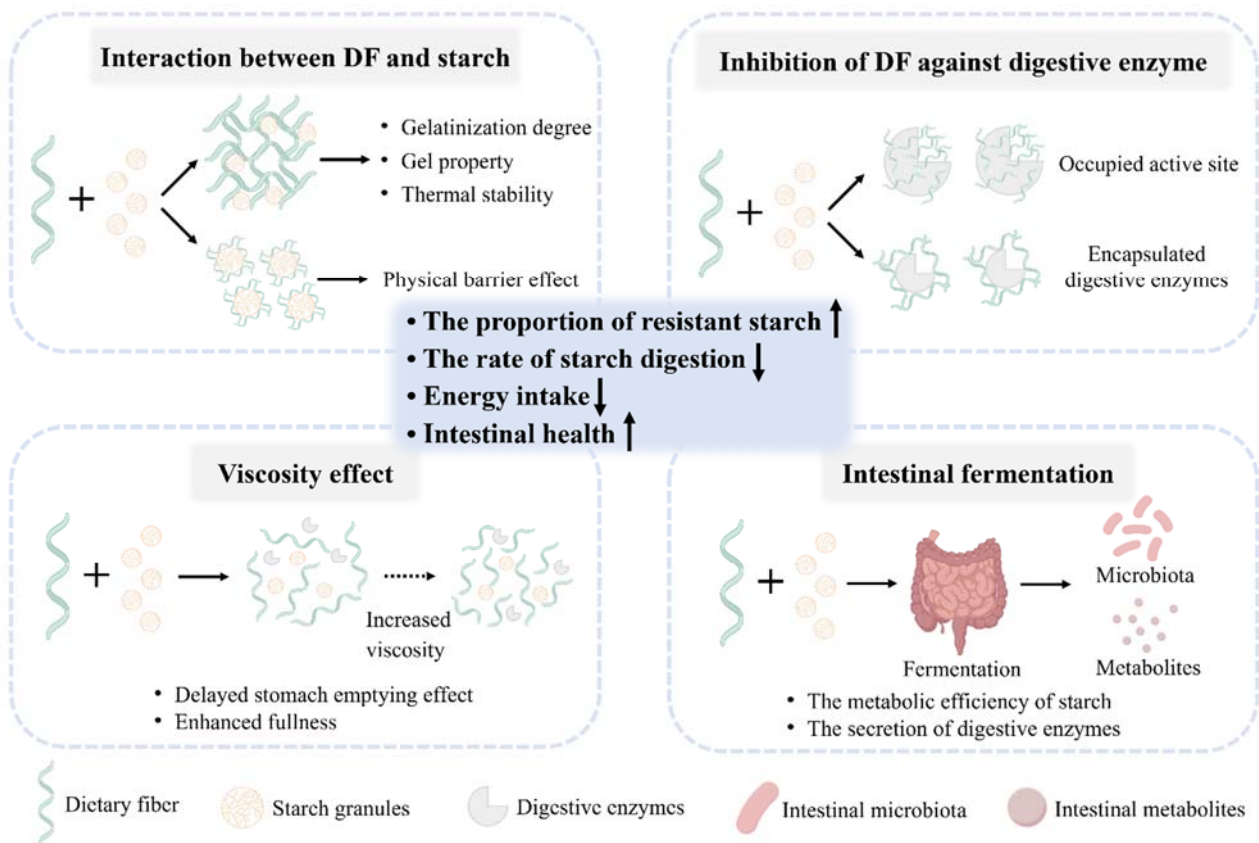


Figure 3 The possible mechanism on the inhibition of DF on starch digestion

4.1 The interaction between DF and starch

DF can suppress starch digestion through direct interactions with starch itself, acting either by altering the physicochemical properties of starch or by physically encapsulating starch granules. The interaction between DF and starch can alter the molecular structure, aggregation state, and interfacial properties of starch in various ways, thereby systematically regulating its digestion behavior. Research has demonstrated that konjac glucomannan can form V-shaped single helical inclusion complexes with amylose through hydrophobic interactions, which increased the steric hindrance at the α -1,4 glycosidic bond cleavage sites⁸⁶. Furthermore, the hydroxyl groups in DF form hydrogen bond networks with the α -1,6 glycosidic bonds at the branch points of amylopectin, thereby hindering amylase's attack on the branched regions¹³. Collectively, these mechanisms impede starch hydrolysis and consequently slow its digestion.

The digestion property of starch is closely related to its gelatinization/gelation and retrogradation/aging processes. DF may accomplish the objective by suppressing the gelatinization process while facilitating retrogradation. The elevated water retention ability of DF enabled it to vie for accessible water within the system, therefore inhibiting starch from completely absorbing water and expanding. This mechanism reduced the degree of gelatinization and facilitated the retention of a greater amount of RS, specifically RS1 and RS2⁸⁷⁻⁸⁸. This phenomenon was particularly evident in DF with high molecular weight. Some RS can act as crystal nuclei, promoting the rearrangement of amylose, accelerating starch retrogradation, and forming RS3, thereby slowing down the digestion process⁸⁹. Gum guar, carrageenan, β -glucan, konjac glucomannan, locust bean gum and other water-soluble colloids, when mixed with starch, can slow down the

aging rate of starch paste during the freezing process, and reduce the digestion of starch^{49, 77, 90}. Xanthan gum, sodium carboxymethyl cellulose and carrageenan at addition concentrations of 0.15%, 0.25%, 0.35% and 0.45% influenced the gelatinization, thermal properties and rheological properties of cassava starch. Among them, xanthan gum exhibited a pronounced interaction with cassava starch, successfully infiltrating the starch granules. This interaction led to an increase in the viscosity during starch gelatinization, enhanced swelling power, as well as improvements in both storage modulus and loss modulus, while simultaneously reducing the degree of starch retrogradation⁹¹.

Physical encapsulation is a second, closely related route through which DF constrain starch digestion. IDF, particularly cellulose and hemicellulose, can envelop starch granules through a physical barrier effect. This encapsulation limits the swelling and gelatinization of starch, thereby reducing the availability of amylase. This encapsulation relies on non-covalent interactions (hydrogen bonds, van der Waals forces, and electrostatic attractions) that promote chain entanglement and the formation of denser, more ordered gel networks¹³. During the gelatinization of starch, xanthan gum and guar gum can coat the surfaces of corn starch particles, competing with starch for water absorption^{81, 92}. Pectin had the ability to encapsulate starch granules, thereby protecting them from swelling and enzymatic action⁷⁹. Similarly, the proton exchange between hydroxyl groups and water, as well as the hydration of β -glucan, competed with starch for available water, which restricted the gelatinization process and reduced the digestion of the food matrix⁸³. Furthermore, DF-encapsulated starch enhanced its structural integrity and maintained its crystallinity to a certain extent. The crystallinity of starch contributed to its resistance against enzymatic hydrolysis by masking enzyme active sites and obstructing their interaction with enzymes, thus indirectly affecting starch digestion⁷. Notably, research indicated that konjac glucomannan increased the short-range ordered structure of starch while xanthan gum enhanced its relative crystallinity¹². Another study indicated that modest concentrations of guar gum markedly maintained the crystallinity and short-range ordered structure of lotus seed starch gel. Conversely, higher doses of guar gum reduced crystallinity while enhancing both swelling power and RS content⁹². Furthermore, experiments conducted by Liu et al. demonstrated that the incorporation of IDF from rice bran altered the peak values of diffraction patterns associated with the starch crystalline structure, resulting in a substantial enhancement in relative crystallinity. High-viscosity DF often exhibited film-forming or coating properties, effectively filling gaps between starch granules or enveloping them. This action inhibited amylose leaching and protects starch granules from gelatinization⁴⁸. Additionally, the interaction between DF and other macromolecules can induce a physical embedding effect on starch. For instance, Nguyen et al. demonstrated that the connection between β -glucan from oats and proteins led to a strong binding of the protein fiber structure in noodles enriched with oats, acting as a physical barrier against digestive enzymes and consequently diminishing the digestion of starch⁹³. Certain SDF can form stable complexes with amylose through hydrogen bonds or hydrophobic interactions. These complexes exhibited resistance to amylase activity and delay the hydrolysis of starch. In high-viscosity systems, β -glucan interacted with starch molecules to create a physical barrier that impedes enzyme access

to starch⁷⁰. Furthermore, phenolic acid groups presented in arabinoxylan can covalently cross-link with starch, further diminishing its digestion⁹⁴.

In recent years, the interaction between DF and starch has emerged as a significant research focus. However, most studies have primarily concentrated on the effects of their mixing on the physicochemical properties of starch, with only a limited number of investigations exploring its influence on digestion and the relationship between these physicochemical properties.

4.2 Inhibition of DF against the digestive enzyme activity

Beyond their well-known physical barrier effects, DF can also curtail starch digestion by directly dampening the activity of digestive hydrolases, especially α -amylase and α -glucosidase. The magnitude of this inhibition varies with the fiber type and its concentration⁹⁵. Early work by Slaughter et al. demonstrated that galactomannan bond to α -amylase and acts as a non-competitive inhibitor⁸⁵. Cross-linked arabinoxylan, by contrast, was reported to quench α -glucosidase activity in a static manner while unexpectedly increasing α -amylase activity; its inhibition of α -glucosidase was likewise non-competitive⁹⁴. IDF from wheat bran has been shown to contribute to lower postprandial glycaemia, at least in part through direct suppression of α -amylase⁴². Moreover, lignosulfonic acid was shown to inhibit the uptake of 2-deoxyglucose in human colorectal cancer cells. The fecal sugar content of rats fed a diet supplemented with 5% lignosulfonic acid was higher than that observed in the control group. These findings suggested that lignosulfonic acid may inhibit increases in blood glucose levels by suppressing α -glucosidase activity and reducing gut glucose absorption⁹⁶.

The interplay between DF and other food components can further modulate these enzyme-inhibitory effects, sometimes weakening them. For instance, arabinan and polygalacturonic acid formed ternary complexes with epigallocatechin gallate (EGCG) and α -glucosidase, thereby attenuating the competitive inhibition that EGCG would otherwise exert. This attenuation was thought to arise from the short side chains of arabinan, which favored EGCG binding, combined with the highly polar carboxyl groups on the fiber that promoted hydrogen bonding with EGCG⁹⁷. Likewise, pectin can interact with phenolic compounds such as rutin and mulberry polyphenols. At low concentrations, pectin actually diminished the inhibitory actions of rutin, quercetin, and kaempferol toward α -glucosidase; however, at higher concentrations this effect reversed, possibly because excess pectin formed complexes with the enzyme itself⁷⁸.

Recent molecular docking studies have shed light on the direct interactions between DF and digestive enzymes. Konjac glucomannan, for instance, has been shown to occupy the catalytic pockets of both α -amylase and α -glucosidase simultaneously, anchoring itself through a stable network of hydrogen bonds⁹⁸. Likewise, *Hericium coralloides* polysaccharide acted as an effective and specific ligand for α -glucosidase⁹⁹. Docking analyses of lentinan revealed that all four of its structural forms bond to the allosteric channels or adjacent cavities of α -glucosidase via electrostatic interactions and hydrogen bonds, exhibiting a non-competitive inhibition pattern; notably, the presence of (1→6)-glycosidic linkages appeared to favor binding affinity¹⁰⁰. Collectively, these molecular simulation studies have established a mechanistic

framework in which DF directly intervene in starch hydrolysis, by occupying catalytic or allosteric sites on the enzymes, or by forming stable complexes with them. These *in silico* approaches thus serve as an indispensable tool for deciphering the structural determinants of DF-enzyme recognition.

4.3 Viscosity reduces starch decomposition kinetics and delays gastric emptying

During oral processing, several studies have indicated that increasing the duration or intensity of food exposure in the mouth can enhance the generation of satiety signals and assist in regulating subsequent energy intake^{3, 13}. The degree of oral exposure is affected by the textural attributes of food, with viscosity being a crucial physical trait that warrants attention. Foods with high viscosity that are rich in DF may enhance mastication, prolong the duration of oral exposure, and increase the frequency of chewing cycles prior to deglutition. Viscous DF elevates the viscosity of gastrointestinal contents after ingestion, thereby extending both transit and digesting times within the gastrointestinal system⁷¹. This retardation reduces the rate at which starch is delivered to the small intestine, thereby blunting glucose release⁷¹. Consistent with this, Chen et al. assessed the impact of various viscous SDF including xanthan gum, guar gum, locust bean gum, hydroxypropyl methylcellulose, and psyllium, on starch digestion rates in both initial low-viscosity and high-viscosity liquids. At the 10 min mark, glucose release in the dialysate was found to be negatively correlated with system viscosity. The five types of gums considerably hindered glucose diffusion and restricted starch hydrolysis rates at elevated viscosities; however, they exhibited minimal effects on digestion under low-viscosity conditions¹⁰¹. Additionally, nanometer-sized chitin fibers demonstrated high viscosity levels that increased digestive juice viscosity while constraining its flow within the intestinal cavity, thereby diminishing overall digestibility^{41, 55}.

Beyond the direct effect on gastric emptying, the increased viscosity also prolongs intestinal transit time, which enhances the contact between nutrients and the intestinal mucosa. This interaction promoted secretion of appetite-related hormones including glucagon-like peptide-1 and peptide YY¹⁰². These hormones were recognized as key regulators of satiety; they exerted their effects on brain function via the brain-gut axis, thereby enhancing feelings of fullness¹⁰². This satiety-enhancing effect, together with the physical slowing of gastric emptying, contributed to a reduced consumption of starchy foods and indirectly lowered the total glycemic load. Consequently, this procedure enhanced satiety and decreased the consumption of starchy foods¹⁰³. Importantly, the efficacy of this viscosity-mediated mechanism varies with fiber type and processing: SDF generally exerts a stronger impact than IDF, and extensive processing tends to weaken the inhibitory effect.

4.4 Regulation on intestinal flora and its metabolites

DF not only influences starch digestion through the aforementioned mechanisms but also indirectly regulates carbohydrate digestion and absorption by modulating gut microbiota and its metabolites. Recent advancements in microbiomics have demonstrated that DF consumption can significantly alter the composition of gut microbiota, enhance the proliferation of specific microorganisms, and produce

metabolites such as SCFAs, thereby impacting the host's glucose metabolism and the efficiency of starch digestion.

DF, especially fermentable fiber, including RS, inulin, and fructooligosaccharides, serves as an important energy source for intestinal microorganisms. These DF are difficult to be broken down by digestive enzymes in the upper digestive tract, but once they reach the colon, they can be fermented and utilized by specific bacterial groups such as *Bifidobacterium*, *Lactobacillus*, *Prevotella*, and *Roseburia*¹⁰⁴. Research has demonstrated that a high-DF diet can significantly enhance the abundance of beneficial microbiota while inhibiting the growth of potentially pathogenic microbiota. This process helped regulate gut microbiota and optimized the microecological balance within the gut¹⁰⁵. Certain gut microbiota is capable of modulating enzymes involved in starch digestion. For instance, *Bacteroides* can secrete α -glucosidase inhibitors that competitively inhibit the activities of maltase and sucrase at the brush border of the small intestine, thereby reducing the absorption of starch decomposition products¹⁰⁶. Additionally, *Akkermansia* played a crucial role in enhancing gut barrier function and mitigating gut inflammation, which subsequently improved insulin sensitivity and indirectly influenced starch metabolism. The primary fermentation products derived from DF by gut microbiota were SCFAs, including acetate, propionate, and butyrate. These metabolites can impact starch digestion and glucose metabolism through various pathways. Notably, propionate has been shown to diminish pancreatic α -amylase secretion, consequently slowing down the rate of starch degradation²¹. Butyric acid acts on L cells in the intestinal epithelium by activating G protein-coupled receptors on their surface, thereby promoting the release of glucagon-like peptide-1 and peptide YY. These two hormones are known to slow gastric emptying through inhibition of gastric motility and pyloric relaxation¹⁰⁷. The resulting delay in gastric emptying limits the rate at which starch is delivered into the small intestine, so that starch enters more gradually leading an effect that prevents a rapid surge in glucose release and subsequent absorption²¹. Additionally, butyric acid can modulate the hepatic gluconeogenesis pathway. Upon entering the portal vein, propionic acid can inhibit glucose output from the liver, reduce endogenous sugar release, and indirectly mitigate fluctuations in blood glucose level²¹.

Studies have shown that Konjac DF enhanced satiety and regulated the latter stages of digestion by delaying gastric emptying, inhibiting starch hydrolysis in the small intestine, and promoting the production of SCFAs in the colon, as well as the proliferation of probiotics including *Lactobacillus* and *Bifidobacterium*¹⁰⁸. Similarly, adding arabinoxylan to bread/cookies dose-dependently transferred more starch and protein through the gastrointestinal tract to the colon, thereby positively modulating the gut microbiota by increasing the carbohydrate/protein ratio and enhancing the relative abundance of probiotics (*Bifidobacterium* and *Lactobacillus*) and SCFA levels¹⁰⁹. Additionally, DF cookies containing xanthan gum, konjac glucomannan, or arabinogalactan similarly demonstrated the ability to modulate microbial structure, increase *Bifidobacterium* and *Lactobacillus* counts, and boost SCFAs production in *in vitro* fermentation models⁸¹. Collectively, these results indicated that DF can comprehensively act throughout the stomach-small intestine-colon digestive segments, particularly by promoting probiotic proliferation and

metabolism, thereby reducing the overall bioavailability of starch and providing an important mechanistic basis for the development of low-GI foods.

Due to the variations in gut microbiota composition among individuals, the inhibitory effect of DF on starch digestion can differ significantly. Individuals adhering to a long-term high-fiber diet may possess a more adaptable gut microbiota, which ferments DF more efficiently and produces higher levels of SCFAs, thereby markedly slowing down starch digestion. Conversely, individuals adhering to a low-DF diet may be deficient in crucial fermentative strains within their microbiota, resulting in a reduced efficacy of the intervention. DF is essential in impeding starch digestion and postponing glucose absorption via influencing the gut flora and its metabolic byproducts. This mechanism provides new perspectives for formulating intervention methods aimed at diabetes and obesity via prebiotics or DF. Future studies should further examine the connections between different forms of DF and unique microbiota to further individualized nutritional intervention strategies.

5. Application of DF on slowing down starch digestion in the food industry

As an essential seventh nutrient, the role of DF in regulating starch digestion is particularly noteworthy. Through various mechanisms, such as delaying gastric emptying, forming physical barriers, and modulating gut microbiota, DF effectively slows starch digestion and glucose release. This presented innovative strategies for dietary interventions in metabolic diseases, including diabetes and obesity. The rising demand for low GI meals underscores the significant potential for research into the interaction mechanisms and regulatory techniques between DF and starch in the production of functional foods (**Figure 4**).

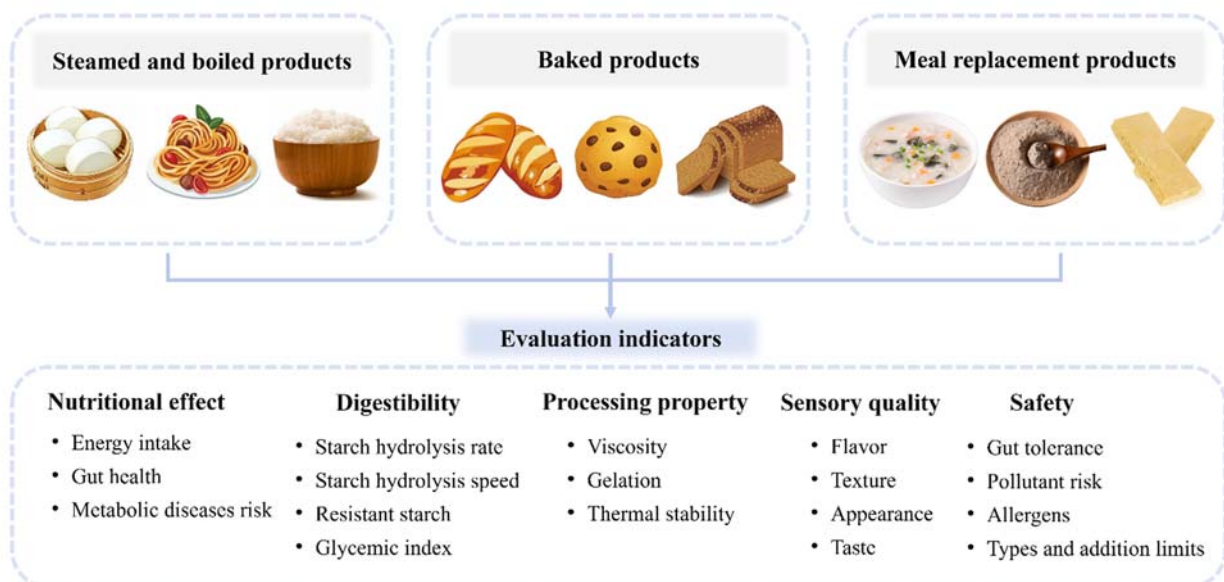


Figure 4 Application on the inhibition of DF on starch digestion in the food industry

6.1 Steamed and boiled food

Research has demonstrated that incorporating of psyllium seed powder and psyllium husk powder into traditional rice flour can significantly decrease starch digestion. Compared to the estimated GI (eGI) of

86.69 for conventional white rice flour, the eGI values for rice flour containing 5% psyllium husk powder and an additional 2% psyllium seed powder decreased significantly to 66.74 and 65.77, respectively, achieving a medium GI categorization. This reduction was ascribed to the increased DF content in both psyllium and its husk, which enhanced starch crystallinity¹¹⁰. Similarly, using basic wheat flour steamed buns with an eGI value of 88.16 as a control group, it was observed that incorporating 7% soybean DF and 3% brown rice DF separately resulted in a significant decline in the eGI values of the steamed buns. Notably, the addition of 7% soybean DF significantly lowered the eGI value of these buns to 79.74, while the incorporation of 3% brown rice DF also decreased the eGI value to 82.95¹¹¹. This study confirmed that the addition of an appropriate amount of DF from soybean or brown rice can effectively regulate starch digestion, thereby reducing the GI value of steamed buns. Importantly, the postprandial glucose-lowering effect of soybean DF was found to be superior to that of brown rice DF at equivalent addition levels¹¹¹. However, it is essential to recognize that not all varieties of DF were beneficial in reducing the glycemic index of starch. Research has shown that buckwheat DF, due to its high SDF content, formed a looser structure with starch molecules during processing. This alteration undermined the original anti-digestive properties inherent in starch. Consequently, after incorporating buckwheat DF, the eGI value of steamed buns significantly increased to 66. This outcome sharply contrasted with the effects observed from soybean and brown rice DFs. These findings clearly indicated that the impact of DF on the digestive qualities of starch is intricately associated with their physicochemical characteristics; furthermore, SDF and IDF may exhibit entirely opposite effects when regulating starch digestion¹¹¹. Nguyen et al. reported that incorporating whole oat flour into wheat noodles markedly reduced starch digestibility. The β -glucan in oats was found to interact with wheat proteins, forming a physical barrier that impeded digestive enzymes and altered their microstructure⁹³. Without compromising the edible quality of rice noodles, IDF from rice bran was added to the noodle formulation at concentrations ranging from 3% to 12%. Notably, the 3%-9% additions substantially delayed starch hydrolysis during *in vitro* digestion, with the sample containing 3% exhibiting optimal anti-digestive performance. Among various types of DF tested, hemicellulose demonstrated the most effective inhibition of glucose diffusion, followed by lignin and cellulose⁴⁸.

Subsequent study has shown that different specialized DF exhibits unique regulatory effects on the starch digesting characteristics of cooked meals. The incorporation of mushroom powder can substantially alter the starch digestion characteristics of wheat-based products. This alteration was attributed to its high DF content, which effectively inhibited amylase activity, thereby reducing the extent of starch degradation and limiting the release of reducing sugars¹¹². Meanwhile, the addition of sorghum bran operated through a different mechanism. Its rich polyphenol and cross-linked starch content can enhance the formation of RS, increasing RS levels in steamed buns and consequently delaying starch digestion significantly¹¹³. Moreover, IDF derived from *Acca sellowiana* has been shown to have a notable impact on blood glucose management in steamed bread products. When incorporated at a level reaching 4%, this DF effectively reduced glucose adsorption capacity within the starch matrix of steamed bread, attributable to its distinctive physical

structure and adsorption characteristics ¹¹⁴. The application of wheat bran DF demonstrated particularly significant effects. When incorporated at a rate of 10%, the starch hydrolysis rate in millet steamed buns decreased from 60.72% to 40.83%. This reduction can be attributed primarily to the pore structure of wheat bran fiber, which encapsulated the starch particles, along with its high water-binding capacity. These properties jointly impeded the interaction between starch and digestive enzymes, ultimately obstructing the entire gelatinization process of starch ¹¹⁵. These findings offered a diverse range of DF options for the development of functional cooked foods.

6.2 Baked products

DF finds extensive application in baked products for its capacity to modulate starch digestion. Psyllium fiber, recognized for its remarkable water-retention ability, may form a substantial physical barrier within the dough, effectively hindering enzymatic starch breakdown in wheat bread. In contrast, psyllium has little effect on starch gelatinization, unlike cellulose, which induces marked changes in gelatinization behavior ^{73, 116}. Conversely, the SDF present in rice bran exhibited a different mode of action. It effectively delayed the gelatinization process of starch in biscuits and inhibited the digestion and hydrolysis of starch by increasing the viscosity of the system and promoting the formation of a gel network ⁶⁹. Notably, although the IDF from ginseng can effectively inhibit the release of glucose in bread, it only showed favorable consumer acceptance only at an addition level of less than 4% ¹¹⁷. A comparable effect was observed when wheat flour was partially replaced with watermelon peel powder and high-amylose corn starch in cookie making; this was probably because these fiber sources, being indigestible and cell-wall constituents, impeded gelatinization by both entrapping starch granules and disrupting crystalline structure ¹¹⁸. Special modified DF exhibited more refined regulatory capabilities in baked products. Selenium-modified *Tremella fuciformis* stem SDF formed strong hydrogen bonds and hydrophobic interactions with starch molecules. These interactions not only enhanced the entanglement and overlap degree between molecular chains but also promoted the formation of a gel network structure with smaller pore size and more uniform distribution. Simultaneously, the altered DF immediately adhered to the starch particles by surface adsorption, therefore markedly reducing both the leaching rate and the enzymatic hydrolysis rate of starch ⁶⁷. Similarly, papaya DF, malt DF, chitin and codfish shells also delayed starch digestion through physical entrapment and molecular entanglement ¹¹⁹⁻¹²¹. The *Pleurotus sajor-caju* powder reduced the sensitivity of starch to digestive enzymes and significantly lowers the GI value of biscuits by altering the morphological characteristics of starch granules, reducing their particle size and inducing the formation of irregular shapes ¹²². These findings offer a diverse palette of raw materials for developing baked goods with precisely tailored nutritional profiles.

Arabinoxylan can form complexes with starch through its branched molecular structure, increasing the RS content in baked products. These RS can effectively resist digestion in the small intestine and enter the colon intact for fermentation. *In vitro* fermentation experiments have confirmed that this process can significantly alter the structure of the gut microbiota, making beneficial bacteria such as *Bifidobacterium*

and *Lactobacillus* the dominant microbiota, while promoting the production of SCFAs¹⁰⁹. This “digestive regulation-intestinal health” dual-effect model breaks through the functional limitations of traditional baked products as merely a source of energy, providing an innovative approach for the development of dual-effect baked products that can both regulate blood sugar and promote gut health.

6.3 Meal replacement products

In recent years, DF has attracted considerable interest in the development of meal replacement foods, largely owing to its ability to modulate starch digestion and promote satiety. Daniel et al. found that psyllium powder was abundant in indigestible carbohydrates, especially RS2. This unique starch configuration allowed it to resist degradation by small intestinal digestive enzymes. When incorporated to a composite yogurt system, psyllium powder significantly reduced the *in vitro* starch digestibility of the product through its distinctive viscous polysaccharide network⁵⁴. Similarly, banana fiber, papaya fiber and kale fiber also exhibited the comparable effect. These DF slowed down the digestion rate by physically embedding starch molecules or forming gel network structures, thereby hindering the action of amylase¹²³⁻¹²⁴. Such a mechanism is particularly valuable in meal replacement applications, as it initially lowers the rate of enzymatic starch hydrolysis, thereby prolonging glucose release. A more stable glycemic profile may, in turn, substantially reduce the risk of postprandial hyperglycemia in diabetic individuals. Additionally, a consistent calorie supply aligns more closely with the physiological requirements of individuals managing their weight. The research conducted by Liu et al. provided empirical support for this assertion; when oat bran and naked oat bran were incorporated into meal replacement drink powder, the postprandial blood glucose peak in healthy subjects was substantially decreased¹²⁵. This finding indicated that the judicious selection of high-DF materials in meal replacement food formulations can optimize their glycemic regulation properties.

In addition to regulating the digestion rate, DF can also improve the texture characteristics of meal replacement foods. For instance, when banana by-product DF was incorporated into meal replacement yogurt, it not only slowed down the digestion rate of starch through a fibrous network structure but also significantly improved the rheological properties of the product due to its unique fiber skeleton. This resulted in a reduction in dehydration shrinkage and an increase in apparent viscosity, thereby achieving a more stable system structure and a smoother texture¹²⁰. Likewise, fibrous components such as psyllium powder and wheat bran can strengthen the gel network structure, providing meal replacement foods including porridge, milkshakes, or energy bars, with enhanced viscoelasticity and chewiness. This enhancement facilitated increased customer acceptability. The main aim of meal replacement meals was to extend fullness and reduce superfluous snacking. Clinical research conducted by Oladiran et al. provided direct evidence supporting this claim: utilizing a double-blind crossover trial design with 200 g/kg of micronized wheat bran added to cassava-soy-based meal replacement porridge, 15 healthy subjects were monitored for 3 h. The results demonstrated that those in the high-DF group had markedly less hunger symptoms, validating that wheat bran considerably improves satiety⁷². This effect may be attributed to DF's

high water-holding capacity, which increased chyme viscosity and delayed gastric emptying, thereby extending feelings of fullness.

6.4 Consumer demand and acceptance of the above-mentioned products

With the continuous enhancement of health awareness, there has been a notable rise in consumer acceptance and demand for “high DF” and “low-GI” products. Market study revealed that around 72% of customers choose “high DF” and “low-GI” as the foremost criteria when choosing meal replacement products. The data sourced from the website “<https://www.marketgrowthreports.com/market-reports/low-gi-food-market-102637>”. This preference was especially evident among pre-diabetic individuals and fitness enthusiasts. Notably, products with high DF content often struggle to maintain palatability. Consequently, using microencapsulation technology to enhance the coarse texture of fiber may be a judicious strategy.

An effective approach is enhancing the sensory attributes of starch-based meals by meticulous regulation of DF incorporation. For instance, incorporating 6% rice bran DF resulted in cookies that received favorable acceptability and texture scores from consumers. The inclusion of rice bran DF had relatively minor impacts on the odor, taste, and color of the cookies ⁶⁹. Similarly, studies on resistant dextrin within bread systems demonstrated a clear dose-dependent effect; at an addition level of 3%, only minimal sensory differences were observed, which remained acceptable to consumers. However, increasing this level to 10% led to significant deterioration in both texture and flavor, resulting in a sharp rise in consumer rejection rates ¹²⁷.

Although the addition of DF often causes changes in the sensory characteristics of products, these changes do not necessarily affect overall acceptability. High levels of *Psyllium* DF, although altering bread color, moisture, and adhesiveness, did not significantly reduce overall consumer preference ⁷³. Similarly, sorghum bran bread scored lower in texture and taste, yet its low-GI properties still maintained consumer purchase intention ¹²⁴. On the other hand, a moderate addition (4%–8%) of *Tremella fuciformis* stem DF helped improve the shape and texture of cookies, thereby enhancing overall sensory quality; however, excessive addition introduced grittiness and uneven structure, resulting in a significant decline in sensory scores ⁶⁷. Overall, the effect of DF in baked products highly depends on its added amount, with moderate addition capable of providing functional properties while maintaining or enhancing sensory acceptability.

Moreover, female customers aged 18 to 45 had the highest propensity to spend for these items. The data sourced the web “<https://www.marketgrowthreports.com/market-reports/low-gi-food-market-102637>”. They specifically like products that claim advantages for weight control and gastrointestinal wellness. This consumption trend is propelling advancements in “high DF” and “low-GI” foods designed to achieve precise blood sugar regulation through innovative fiber blending technologies while preserving desirable texture and flavor. However, such products still face multiple challenges in the process of commercialization: on one hand, they need to meet strict regulatory requirements; on the other hand, they must balance cost control with sensory quality to avoid diminishing consumers’ willingness to purchase due to rising raw material or

processing costs. Therefore, developing low-GI foods that combine health benefits with a good sensory experience remains an important direction for the future development of the food industry.

7. Conclusions and future prospects

Regulating the digestion process of starch in food represents an effective strategy for controlling postprandial blood glucose levels, which is essential for the prevention and management of metabolic diseases such as obesity, hyperglycemia and T2DM. Among the various food components, DF has drawn particular attention in food science owing to its distinctive physicochemical attributes and physiological effects. This review examined how DF retarded the rapid digestion of starch and thereby contributed to lower postprandial glycemic responses. The health benefits of DF were intimately linked to its structure and properties. Pre-treatments applied to DF and the processing conditions of food systems can modify these structural features, potentially reinforcing the inhibitory effect on starch digestion. Multiple mechanisms have been proposed to explain this action. First, DF can interact directly with starch, altering its crystallinity and gelatinization behavior, or physically encapsulate starch granules, thereby enhancing resistance to enzymatic breakdown and favoring the formation of RS. DF may also coat digestive enzymes or bind to their active sites, limiting the accessibility of starch to hydrolysis, which is reflected in reduced *in vitro* digestibility. In addition, certain SDF markedly elevated the viscosity of the chyme, slowed gastric emptying, and promoted a greater sense of satiety. Finally, undigested DF reached the colon, where it enriched the beneficial gut microbiota and stimulated the production of microbial metabolites. Some of these metabolites, in turn, modulate circulating levels of digestive hormones that influence appetite and satiety, thus indirectly affecting blood glucose regulation and the overall digestive process.

Despite extensive research, understanding the complex structure of DF and its interactions with starch remains a challenging and uncertain area. Food is a highly intricate system in which components such as DF, carbohydrates, proteins, lipids, and other nutrients undergo dynamic physicochemical interactions during both processing and digestion. These interactions frequently give rise to binary, ternary, or even higher-order complexes, and the properties of these complexes ultimately dictate the extent of starch digestion. Several key challenges persist in current investigations. First, our knowledge of the formation mechanisms and functional characteristics of ternary complexes involving starch, DF, and other nutrients is still limited. For instance, proteins may interfere with DF-starch interactions through competitive binding¹²⁸, while lipids can alter the spatial conformation of the resulting complexes¹²⁹. There is a clear need for systematic studies that address the formation process, structural features, and the precise influence of these higher-order complexes on starch digestibility. Second, conventional *in vitro* digestion models typically rely on over-simplified systems that do not adequately replicate the complex milieu of actual foods within the human gastrointestinal tract. More physiologically relevant *in vitro* models are required, ones that account for the synergistic effects of multiple food components and the dynamic changes occurring throughout digestion. Moreover, current analytical techniques still face technical limitations when it comes to elucidating the detailed structures of multi-component complexes. Exploring non-thermal processing

approaches for the precise modulation of DF structure may help circumvent the safety concerns associated with traditional chemical modification while retaining the beneficial bioactivity of DF. As research deepens, the potential applications of DF in the development of healthy foods are expected to expand, offering new strategies for dietary intervention in metabolic diseases.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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