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Review Article

An In-Depth Overview of the Structural Properties, Health Benefits, and Applications of Resistant Dextrin

Xiuli Wu, Jianwen Zhang, Xiangxuan Yan, Xuexu Wu, Qing Zhang, and Mingran Luan

College of Food Science and Engineering, Changchun University, Changchun 130022, China

Correspondence should be addressed to Xiuli Wu; wuxl@ccu.edu.cn

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With the escalating prevalence of diabetes and obesity, resistant dextrin, renowned for its prebiotic properties and blood glucose-lowering physiological activity, has garnered significant attention. Resistant dextrin, a low-calorie, indigestible water-soluble dietary fiber processed from starch, has high solubility, low molecular weight, and good thermal stability. The established method for its preparation involves a combination of acid heat treatment and enzymatic purification. Within the human body, resistant dextrin confers numerous health benefits. It promotes a balanced intestinal microbiome, regulates blood glucose and lipid metabolism, and enhances satiety. Additionally, it exerts positive influences on the intestinal environment, aids in weight management, and alleviates chronic conditions, particularly diabetes. In the food industry, resistant dextrin is widely employed as a functional food additive to enhance the nutritional value and health benefits of various food products. However, there is a need for greater clarity regarding the structural characteristics of resistant dextrin and the potential interplay between its structure and physiological activity. This paper comprehensively reviews the preparation methods, structural properties, health benefits, and application areas of resistant dextrin. Additionally, it anticipates future trends in its development. The primary objective of this review is to offer theoretical guidance and fresh perspectives for further research, the innovation of functional products, and the expanded utilization of resistant dextrin.

1. Introduction

With the improvement in people's standard of living and the growing demand for high-quality ingredients, there has been a significant increase in the consumption of high-calorie, high-fat, and refined foods. Unfortunately, this has resulted in a decline in dietary fiber intake, leading to a rise in the prevalence of chronic diseases such as coronary heart disease and diabetes. Statistics reveal that, as of 2021, the global number of adults with diabetes has reached 537 million, and this number is projected to rise to 783 million by 2045 [1]. Nutritionists agree that dietary fiber is crucial for enhancing nutritional status and regulating bodily functions. It is therefore considered the "seventh essential nutrient for humans" [2, 3]. The World Health Organization (WHO) and the Food and Agriculture Organization (FAO) recommend a daily intake of 38 grams (g) of dietary fiber for men and 25 g for women [4]. Different countries have established their own guidelines for recommended dietary fiber intake. For example, the United States suggests an adequate intake of 28 g per day (with an actual intake of 16.5 g/d), while Australia recommends a dietary allowance of 25-40 g per day (with an actual intake of 20.7 g/d). In China, according to the Chinese Nutrition Society's Chinese Dietary Reference Intake (DRIs), the recommended intake is 25-35 g per day (with an actual intake of 17-19 g/d).

As illustrated in Figure 1, there is a marked variability in dietary fiber consumption across different countries. When aligning recommended dietary fiber intake with actual consumption patterns, a significant disparity becomes evident [5, 6]. Consequently, incorporating high-fiber components into food products has emerged as a crucial approach for nutritional enhancement, aiming to guarantee adequate daily dietary fiber intake for the populace.

Figure 1: Dietary fiber intake among countries [6].

Resistant dextrin, also known as indigestible dextrin, is a type of dietary fiber typically derived from starch that has undergone dextrinization and subsequent depolymerization to form unique structures, such as α-1,2 and β-1,6 bonds. These structural features contribute to its "indigestible" nature [7–10]. Additionally, its molecular structure incorporates hydrophilic groups, and its distinctive spatial conformation endows it with remarkable properties, including water retention, viscosity, and stability. Resistant to enzymatic degradation, it can persist in the human gut for extended periods. Like other dietary fibers, resistant dextrin enhances satiety and promotes regular bowel movements. Moreover, it fosters the growth and proliferation of beneficial gut bacteria, maintains intestinal balance, optimizes gut function, and effectively prevents gastrointestinal disorders. It also inhibits cholesterol absorption and bile acid reabsorption in the small intestine and hinders glucose uptake, thereby contributing to blood glucose stabilization and blood lipid regulation [11, 12]. Furthermore, resistant dextrin is a soluble dietary fiber with exceptional solubility and favorable processing properties. It exhibits a slightly sweet taste and resistance to acidity, pressure, heat, frost, browning, and storage, making it an ideal functional ingredient with broad market potential in food applications [5, 13].

This article summarizes the manufacturing of resistant dextrin, its unique structure, applications, and future research. It is aimed at improving the understanding of resistant dextrin processing and uses among researchers and guiding further studies.

2. Preparation of Resistant Dextrin

2.1. Process Flow. Resistant dextrin, also known as pyrodextrin, is a starch derivative [10]. The production process is generally divided into two parts: the preparation of pyrodextrin through the acid heat method and enzymatic hydrolysis and purification. Specifically, the processes include dextrinization, refining, and drying [14, 15], which are schematically illustrated in Figure 2. Initially, the preparation of pyrodextrin occurs through an acid heat method, where a suitable amount of acid solution is added to the starch. This mixture undergoes a high-temperature acid heat reaction, resulting in the formation of pyrodextrin/resistant dextrin. To further decrease the digestibility, the residual starch in the pyrodextrin can be treated with enzymes such as amylase and other hydrolases. Subsequently, a refined product is obtained through a series of purification steps including decolorization, desalination, concentration, evaporation, and spray drying. These refining processes ensure the production of highly purified resistant dextrin products.

The enzyme tolerance of resistant dextrin is affected by multiple factors, such as the source of starch, the content of amylose and amylopectin, granule structure, and degree of polymerization [14]. Extensive research by scholars has delved into the production of resistant dextrin with low digestibility, exploring various dextrinization times and temperatures for diverse plant-derived starches [10, 14, 16, 17]. Table 1 provides a concise overview of recent studies focused on the preparation of resistant dextrin from different types of starch.

2.2. Progress in Physical Treatment for the Preparation of Resistant Dextrin. The preparation of resistant dextrin through acid heat treatment is a time-consuming process that can contribute to environmental pollution. Conversely, physical treatments have gained widespread acceptance due to their cost-efficiency, safety, and efficacy. These methods

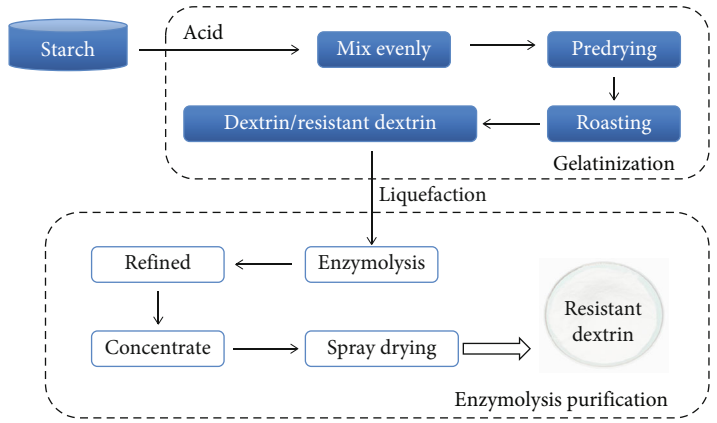

Figure 2: Production flow of resistant dextrin.

Table 1: Preparation of resistant dextrin from a different starch.

Starch sources	*In vitro* digestion (RS)		Molecular weight	References
	Native starch	Resistant dextrin		
Waxy corn	5%	20%-55%	14400 Da	Chen et al. [35]
Sorghum	2.02%	34.23%	—	Chen et al. [17]
Oat	2.02%	32.16%	—	Chen et al. [17]
Potato	5.61%	6.23%-7.32%	3500 Da	Kapusniak et al. [91]
Chinese yam	—	11.8-71.3%	6800 Da	Luo et al. [34]
Cassava	9.9%	24.0%	8-105 kDa	Alexander et al. [14]
Lentil	5.7%	30.4%	8-105 kDa	Alexander et al. [14]
Corn	8.3%	25.2%	8-105 kDa	Alexander et al. [14]
Sorghum	5.7%	20.4%	>105 kDa	Alexander et al. [14]

offer a green alternative that obviates the need for chemical reagents. The availability of starch can be improved by using physical modification methods such as heat-moisture treatment, microwave, and ultrasonic treatments [18, 19].

Microwave technology has emerged as a promising approach in the production of resistant dextrin. It not only improves process efficiency and resolves issues such as uneven heating but also enhances the rate of enzymatic hydrolysis during the purification process, thereby reducing the *in vitro* digestibility of resistant dextrin [20, 21]. Consequently, microwave technology is extensively used in the production of resistant dextrin. For instance, Kapusniak and Nebesny [22] used hydrochloric acid and citric acid treated potato starch and employed microwave heating at 735-1050 W for durations ranging from 2 to 10 min to prepare resistant dextrin. This method significantly reduced the reaction time from hours to minutes, yielding samples with high solubility (approximately 70%) and low viscosity (where the maximum viscosity of a 20% dextrin solution was only 31 Pa·s). In addition, these samples showed minimal retrogradation tendencies and are suitable as additives for soluble dietary fiber and prebiotics in beverages. Additionally, some researchers have explored the impact of discontinuous microwave-assisted heating treatment on the yield and physicochemical properties of resistant dextrin. The findings indicate that the discontinuous process (with 10-fold heating and mixing between cycles) is more effective than continuous heating. The resultant samples demonstrated solubility levels around 80%, albeit with a darker color [23].

While microwave technology is currently less commonly used for preparing resistant dextrin, future possibilities could involve its integration with other physical or chemical techniques, for example, microwave-ultrasonic treatment or combined chemical modification to prepare resistant dextrin. In conclusion, microwave treatment holds significant potential for the development of resistant dextrin, considering the ongoing advancements in various application fields.

2.3. Progress in Chemical Treatment for the Preparation of Resistant Dextrin. Chemical modification can hinder the digestion of replaced fragments and promote intermolecular aggregation, enhancing the yield and benefits of resistant dextrin [24]. Introducing new groups changes the conformation of the starch molecular chain at different scales, reducing its sensitivity to amylase. Consequently, it is difficult to digest [25, 26]. Kamila et al. [24] produced resistant dextrin from potato starch by acidifying the starch with hydrochloric acid combined with either citric acid or tartaric acid. They observed that the molecular weight (Mw) of tartaric acid dextrin (1800 g/mol) was significantly lower than that of citric acid dextrin (3500 g/mol). In another study, Han

and Lim [27] used octenyl succinic acid (OSA) modified corn starch as the raw material and acidified the sample. The investigation revealed that the introduction of new groups in the starch decreased the likelihood of specific binding with amylase, thus reducing its sensitivity to the enzyme. Furthermore, OSA imparted amphiphilic characteristics to the resistant dextrin, improving the emulsification performance of the esterified dextrin. These findings open up possibilities for the application of resistant dextrin in various fields.

2.4. Progress in Enzyme Treatment for the Preparation of Resistant Dextrin. Current research on resistant dextrin extends beyond the traditional use of amylase in its production, exploring variations in enzyme types, reaction conditions, temperature, and duration. Li et al. [28] conducted a comparative study examining the effects of three distinct preparation methods using corn starch as the raw material: the acid heat method, the α-amylase (>4000 U/g) method, and a combination of α-amylase and transglutaminase (6000 U/g). Their findings revealed that resistant dextrin prepared under different conditions exhibited exceptional solubility, achieving nearly 100% solubility in water. Through the synergistic action of α-amylase and transglucosidase, the side chains underwent a glycosidic bond cleavage, resulting in further polymerization and dense interconnection. Consequently, this led to a reduction in chain length and an increase in branching.

3. Characteristics of Resistant Dextrin

The physicochemical properties and structure of resistant dextrin differ significantly compared to those of native starch, and these differences vary depending on the extent of processing.

3.1. Physical and Chemical Properties of Resistant Dextrin

3.1.1. Color. Resistant dextrin exhibits a white or light yellow color distinct from native starches. To obtain a lower *in vitro* digestibility and improved solubility, it is necessary to elevate the concentration of hydrochloric acid, heating temperature, and duration of the process [29]. However, the higher temperature and longer time used in the thermal transformation process can result in a darker color of the resistant dextrin. This darkening may be attributed to the formation of coke or low Mw compounds containing carbonyl groups [30]. In the industrial application of resistant dextrin as a food additive, maintaining the desired color is paramount due to its direct influence on product attractiveness and consumer acceptance. Huang et al. [15] reported that the incorporation of resistant dextrin with 83.4% purity into flour significantly bolstered the dough's viscoelastic properties and augmented the bread's resistance to digestive enzymes. Notably, this addition did not compromise the bread's color or overall appearance, thus preserving the product's sensory quality. However, at higher substitution levels, a deeper yellow tint was observed in cakes, suggesting that exceeding certain substitution thresholds might detract from the product's visual appeal [31]. Achieving the desired color and viscosity of resistant dextrin during production poses challenges. Factors such as the choice of acid catalyst [32–34], and the uniformity of acid distribution within the starch [30, 35, 36] can significantly influence the color of the final product. Lin et al. [30] investigated the physicochemical properties of resistant dextrin prepared from corn starch using hydrochloric acid or acetic acid. Their study demonstrated that pyrolysis at different temperatures yielded products with varying appearances. The degree of color change was influenced by the type and concentration of the acid, as well as the reaction temperature. Higher pyrolysis temperatures and catalyst concentrations resulted in a darker product. Therefore, careful consideration of reaction time, temperature, acid concentration, acid type, and acid distribution is crucial to minimize the formation of colored compounds during the production of resistant dextrin.

3.1.2. Solubility. High solubility is essential for the industrial application of resistant dextrin. Native starch is inherently difficult to dissolve, while the solubility of resistant dextrin increases with higher pyrolysis temperatures. Studies have demonstrated that increasing the concentration of hydrochloric acid, reaction temperature, and reaction time can enhance starch hydrolysis, achieving complete solubility for pyrodextrin [35]. Trithavisup et al. [10] investigated the physical, chemical, and thermal properties and molecular structure of cassava resistant dextrin under various dextrinization conditions (0.04-0.10% HCl, 100-120°C, 60-180 min). The findings revealed a significant increase in solubility (up to 99.85%) with higher acid concentration, temperature, and heating time. Furthermore, Lin et al. [30] emphasized the critical role of acid as a catalyst in starch hydrolysis during dextrinization, stating that higher acidity facilitates the process, leading to elevated solubility.

3.2. Structural Characterization of Resistant Dextrin. The structural properties of starch undergo significant changes during dextrinization. This process is influenced by various factors such as the properties of the starch, the type and concentration of the acid catalyst, and the processing conditions. Therefore, it is necessary to employ appropriate methods to ascertain resistant dextrin's apparent morphology and structural properties. Figure 3 summarizes the methods suitable for analyzing the multiscale structure of starch granules at various levels. Scanning electron microscopy (SEM) serves as a widely used tool for examining granule morphology. However, the intricate lamellar organization and hierarchical semicrystalline growth rings necessitate the utilization of small-angle X-ray scattering (SAXS) for a more detailed structural assessment. The ensuing subsections will delve into the methodologies employed to elucidate the features of resistant dextrin.

3.2.1. Apparent Morphological Characteristics of Resistant Dextrin. Polarized light microscopy (PLM) and SEM can be used to observe the microstructure and ascertain the state of resistant dextrin [9, 37]. Each of these microscopy techniques is based on different physicochemical principles and offers unique advantages and limitations (Table 2).

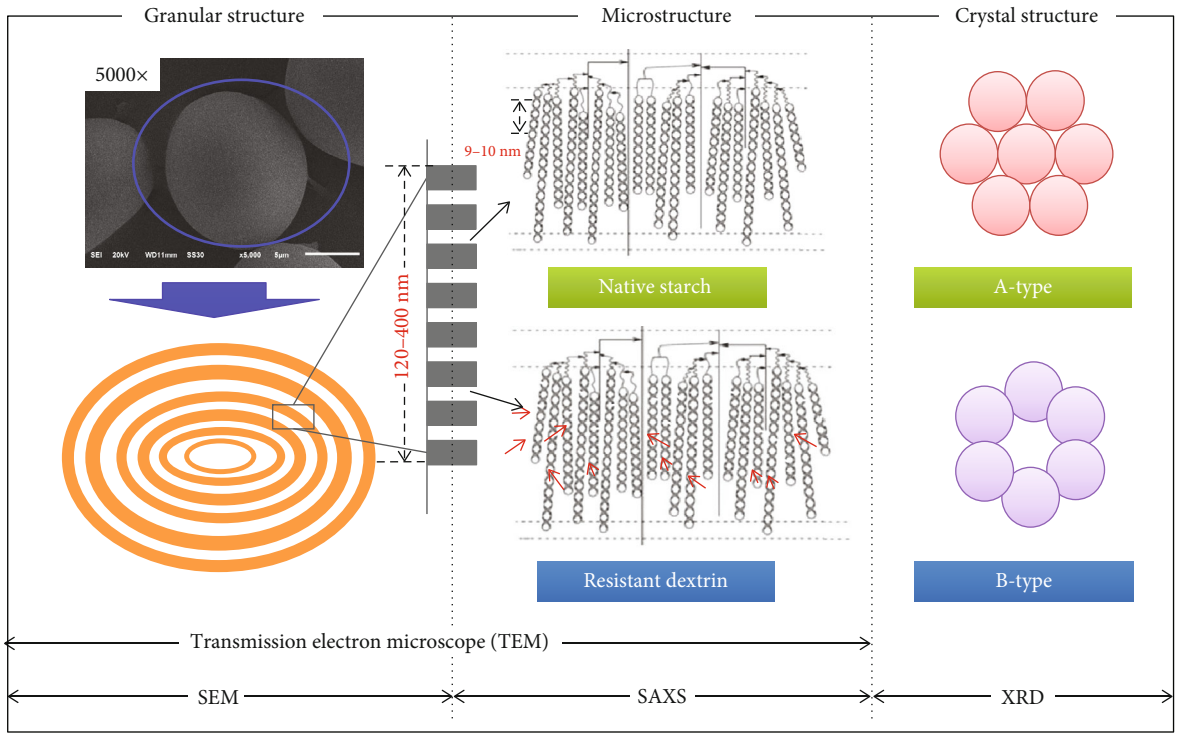

Figure 3: Available assays for the structure of each layer of starch granules.

Table 2: Advantages and limitations of different methods to determine the apparent morphology of resistant dextrin.

Methodologies	Advantages	Limitations	References
PLM	(i) Simple preprocessing procedures and low cost (ii) A quick, clear view of the starch Maltese cross (iii) Visualization of changes in starch structure during the dextrinization process	(i) Only particle morphology can be observed (ii) The size and shape of the obtained starch granules are not precise (iii) To obtain high image contrast requires staining of the sample	Chakraborty et al. [92] Langenaeke et al. [93] Tao et al. [94]
SEM	(i) For studying the shape and surface properties of samples (ii) Relatively easy preparation of specimens (iii) Higher resolution compared to optical microscopes (iv) More stereoscopic imaging	(i) Only give qualitative information on the microstructure, not the fine structure of the sample (ii) Minor differences are not easy to observe (iii) Inability to observe the hierarchical structure of starch	Chakraborty et al. [92] Choudhary & Choudhary [95]

(1) PLM. PLM serves as a tool to observe the apparent morphology of starch. Under PLM, polarization crosses emerge due to anisotropy, which arises from differences in density and refractive index between the crystalline and amorphous structures within starch granules [38]. When observed in glycerol, dextrin persists in a granular state, exhibiting a morphology closely resembling that of the native starch, with polarized crosses and visible umbilical points [30]. Weil et al. [39] suspended starch and dextrin in glycerol and observed Maltese crosses in all samples.

(2) SEM. SEM can provide intricate details on starch granule morphology and surface characteristics [40]. Starches derived from various sources exhibit notable variations in granule shape, size, and surface structure under SEM. For instance, potato starch appears spherical with a smooth surface, corn starch exhibits a polyhedral shape with a rough surface, while mung bean starch displays a kidney-shaped morphology with a smooth surface [41–45]. Li et al. [46] acidified waxy maize starch using HCl and then subjected it to dry heat treatment within a temperature range of 140°C to 200°C. SEM (1000 × magnification) revealed negligible changes in the morphology of the starch granules, indicating their structural integrity after the treatments. Furthermore, the study confirmed the minimal impact of the thermal process on the granular structure, irrespective of the presence or absence of acid [47].

3.2.2. Multiscale Structural Characteristics of Resistant Dextrin. To understand the changes in chemical bonding, Mw, and crystallinity during the preparation of resistant dextrin, various techniques have been used to analyze its structure. These techniques include X-ray diffraction (XRD), nuclear magnetic resonance (NMR), and chain length distribution.

(1) XRD. XRD analysis is primarily utilized to investigate the crystallinity and aggregation state of starch. It is a commonly used technique in starch studies to analyze the type of starch crystallization and to assess changes in crystallinity resulting from modification treatments [48]. Generally, the dextrinization process does not alter the crystalline form of the starch but slightly reduces its degree of crystallinity. This reduction may be attributed to the influence of acid heat treatment, which promotes the repolymerization of small molecules, disturbing the regular arrangement of the molecules and weakening intermolecular forces and hydrogen bonding [42].

SAXS is a structural analysis method distinct from X-ray large angle diffraction (2θ ranging from 5° to 165°). It has been used to characterize starch structures, enabling the examination of nanoscale crystal structures and microstructures. SAXS bridges the gap between modern crystallography and microscopy techniques, providing enhanced spatial resolution. A significant achievement of SAXS in starch science has been the characterization of the lamellar structure within natural starch granules, bridging the analysis of granular and crystalline starch structures [49]. Bai et al. [37] integrated SAXS, SEM, and other technologies to investigate the structural changes that occur during the conversion of waxy corn starch granules into cold-water-soluble pyrodextrins. They proposed a novel model, depicted in Figure 3, to describe the alterations in starch structure during dextrinization. This process involves hydrolysis of the starch skeleton in both amorphous and crystalline regions, leading to reduced crystallinity.

(2) NMR. NMR is a powerful technique for investigating the structure of carbohydrates, including the identification of glycosidic bonds and the determination of α- and β-isomeric conformations [50]. The analysis of ^{1}H-NMR and ^{13}C-NMR has been successfully employed to characterize the glycosidic bonds in D-glucopyranosyl repeat units [51]. The preparation of resistant dextrin involves three main chemical reactions: hydrolysis, transglycosylation, and polymerization. Hydrolysis, catalyzed by acid, breaks the glycosidic bonds in native starch, forming monosaccharides, disaccharides, oligosaccharides, and small molecule dextrin. Transglycosylation occurs after high temperature roasting, where the hydrolyzed fragments recombine with nearby free hydroxyl groups, forming a branching structure. Furthermore, the recombination of small molecules generated by degradation potentially gives rise to the formation of new glycosidic bonds [37]. These new glycosidic bonds contribute to the complex branching structure of resistant dextrin, as depicted in Figure 4. In a study by Han et al. [7], resistant dextrin was prepared from waxy corn starch, and its structure was analyzed using ^{1}H-NMR. The results indicated that the formation of new glycosidic bonds primarily involved α-1,6, β-1,6, α-1,2, and β-1,2 with 1,6-anhydro β-D-glucopyranosyl groups at the end of the starch chains. Bai and Shi [52] also confirmed the generation and composition of new glycosidic bonds in resistant dextrin using the 2D nuclear magnetic resonance (2D NMR) technique.

Therefore, the resistance mechanism of resistant dextrin to enzymatic hydrolysis can be explained by the alteration of glycosidic bonds in starch during the preparation process. The hydrolysis of α-1,4 and α-1,6 glycosidic bonds during dextrinization leads to the formation of α-1,2, β-1,2, and β-1,6 glycosidic bonds. As a result, resistant dextrin becomes unrecognizable by digestive enzymes such as α-amylase and amyloglucosidase, leading to lower *in vitro* digestibility.

3.2.3. Fourier Transform Infrared Spectroscopy (FTIR). FTIR is effective in detecting changes in functional groups in organic compounds and is used to analyze starch structure. Since dextrinization does not introduce new functional groups, the infrared absorption peaks of dextrin are quite similar to those of starch, with both exhibiting typical anhydroglucose characteristics. However, there are still some subtle differences in the details. Specifically, the bands located near 1650 cm^{-1} exhibit variations attributed to differences in the affinity of water molecules within the starch molecule, and the -OH peak near 3400 cm^{-1} undergoes a slight redshift [42]. It is noteworthy that different polysaccharides display unique band positions and intensity characteristics in the fingerprint region of 1000-800 cm^{-1}, providing a robust basis for polysaccharide identification [53]. For example, the characteristic absorption bands at 858 and 932 cm^{-1} reflect the bending vibrations of the C1-H, associated with α- and β-glycosidic bonds [54]. During dextrinization, there is a reduction in the number of α-1,4 glycosidic bonds in starch, leading to a corresponding decrease in the intensity of the bands. Subsequently, transglucosylation and repolymerization reactions occur, resulting in the formation of new glycosidic bonds such as α-1,2 and β-1,2 glycosidic bonds within the molecule [55]. FTIR analysis further confirms the condensation of glucose and the presence of α- and β-glycosidic conformations [55]. These newly generated glycosidic bonds result in lower *in vitro* digestibility of dextrins [56]. Additionally, acid heat treatment disrupts the short-range ordered structure of the starch. The amount of short-range ordered structure (e.g., double helices) is reflected at 1047 cm^{-1}, while amorphous domains are characteristic at 1022 cm^{-1}. The absorbance ratio of 1047/1022 cm^{-1} provides a measure of the degree of order in the crystalline region of the sample [57]. In previous studies, it was observed that the ratio of 1047/1022 cm^{-1} decreased for dextrin samples subjected to acid heat treatment, indicating a change in the composition or structure of the dextrin molecule with a reduction in the ratio of amorphous to the ordered polymer structure [58].

Overall, FTIR analysis provides valuable insights into the structural changes that occur during dextrinization, including modifications in glycosidic bonds and alterations in the short-range ordered structure of starch molecules.

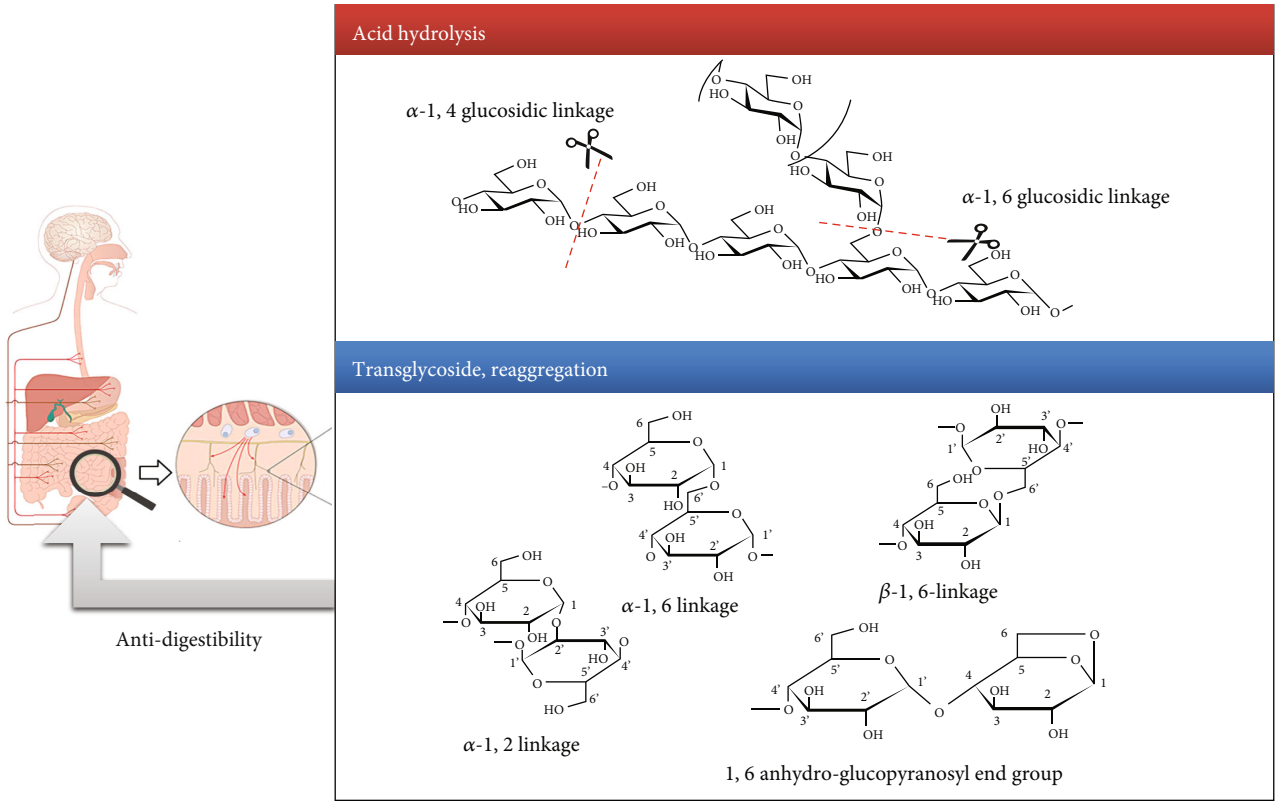

Figure 4: Changes of glycosidic bonds during dextrinization.

3.2.4. Mw. Native starch primarily consists of two distinct biological macromolecules: amylopectin and amylose. Amylopectin is commonly believed to be the main component of starch. The Mw of amylose typically ranges from 10^5 g/mol to 10^6 g/mol, while the Mw of amylopectin is approximately 10^8 g/mol. Both types of starch molecules exhibit heterogeneity in Mw, indicating polydispersity. As a result, the measured Mw of starch represent statistical averages. Common methods for determining the Mw of starch include gel permeation chromatography (GPC), also known as size exclusion chromatography (SEC), asymmetrical flow field flow fractionation (AF4), and the viscosity method. Among these techniques, GPC is considered the most effective for assessing the size of starch molecules based on their Mw or hydrodynamic volume [59]. In a study by Han et al. [7], it was discovered that starch molecules undergo hydrolysis through acid and heat during the dextrinization process. The relative Mw of waxy corn starch rapidly decreased within the first 0.5 to 1 h of the process, after which the rate of change slowed down. The resulting relative Mw ranged from approximately 4.9×10^4 to 2.0×10^5. Mao et al. [60] noted that higher baking temperatures or longer pyrolysis times gradually shifted the highest peak in the sample distribution curve towards smaller molecules. Consequently, the macromolecular region decreased, and the size distribution of the dextrins decreased significantly. These findings suggest that pyrolysis temperature, heating time, and the presence of acid have a substantial impact on the distribution of the relative Mw of dextrin. Contrary to the expectation that Mw invariably decreases with extended heating, this is not always the case. In an investigation by Wang et al. [61] into the preparation of resistant dextrin, it was observed that the Mw initially decreased as heating progressed from 10 to 50 min. Interestingly, after exceeding 60 min of reaction time, an increase in the Mw of the resistant dextrin was noted. This increase may be attributed to the recombination of low Mw fragments generated during thermal degradation. These results highlight the significant influence of factors such as thermal degradation temperature, duration of heating, and the presence of acid on the Mw distribution of dextrin.

3.2.5. Chain Length Distribution. The distribution of starch chain lengths is represented by the degree of polymerization (DP). Amylopectin is characterized by a DP ≤ 100, whereas amylose exhibits a DP ranging from 100 to 10,000. However, dextrin displays an irregular size distribution [62]. It has been observed that the hydrolysis products of pyrodextrins exhibit lower relative Mw and shorter chain lengths. Furthermore, during high-temperature heat treatment, shorter branched chains undergo polymerization, leading to the formation of indigestible fractions. Mao et al. [60] conducted a study in which dextrins were produced through the thermal transformation of native corn starch, both with and without HCl treatment. The findings showed that the size distribution of pyrodextrins significantly decreased with the incorporation of HCl or prolonged heating time. Within the dextrin samples, amylose chains with a DP > 400 became undetectable after heating for 3 and 5 h, indicating complete

degradation of the long amylose chains. Concurrently, there was a notable increase in the reduction of chain length for DP 24-400, particularly for DP 6-12 and 12-24. These observations suggest that both baking temperature and pyrolysis duration have a substantial impact on the distribution of chain lengths within starch.

3.2.6. Thermal Properties. There is a strong correlation between the thermodynamic and physical properties of starch-based foods. Notably, resistant dextrin derived from different sources exhibits significant correlations in structural characteristics and thermal properties [7]. To gain a deeper understanding of these properties, researchers often employ thermal gravimetric analysis (TGA) to assess the thermal stability of samples by measuring changes in mass with temperature. The weight loss curve of resistant dextrin is typically divided into two phases: the first phase corresponds to water loss (between 25 and 150°C), while the second phase is associated with the thermal degradation process (ranging from 200 to 400°C). Remarkably, the structure of resistant dextrin remains relatively stable up to 200°C [63].

Furthermore, differential scanning calorimetry (DSC) serves as a valuable analytical tool, providing crucial thermodynamic parameters for starch during the pasting process. These parameters are essential for comprehending the pasting behavior, stability, and processing properties of starch. Trithavisup et al. [10] conducted a thermodynamic characterization of cassava resistant dextrin using DSC. Their findings revealed that the onset temperature (To), peak temperature (Tp), conclusion temperature (Tc), and enthalpy (ΔH) of the resistant dextrin prepared under milder hydrochloric acid conditions were lower compared to native starch. However, when dextrinization was performed under high acid concentration conditions, the heat absorption peak disappeared. This suggests that mild conditions may not be adequate to completely disrupt the ordered structures of starch, but these structures are substantially weakened in comparison to native starch. Conversely, higher acid concentrations, temperatures, and extended treatment times can lead to more intense hydrolysis and transglycosylation, ultimately resulting in the complete loss of ordered structures. This phenomenon was corroborated by Weil et al. [39] and aligns with the high solubility properties of resistant dextrin.

4. Health Benefits of Resistant Dextrin

4.1. Regulating of Blood Glucose. In recent decades, the prevalence of diabetes mellitus and its complications has escalated, establishing it as a major global chronic illness. Within this landscape, resistant dextrin has attracted much attention as a substance that effectively regulates blood glucose. Clinical studies have confirmed that resistant dextrin has a significant ameliorative effect on type II diabetes. It improves patients' blood glucose and lipid levels, lowers systolic blood pressure, improves atherosclerotic index, and reduces inflammatory response. It is safe with no side effects [64]. Thus, resistant dextrin plays a crucial role in the treatment of type II diabetes and its complications. As a dietary supplement, it reduces the inflammatory response in subjects and animals, diminishes insulin resistance, and mitigates the risk of obesity. Aliasgharzadeh et al. [11] revealed the mechanism of action of resistant dextrin: it significantly reduced fasting insulin levels and homeostatic model insulin resistance index in type II diabetic patients. Its possible anti-inflammatory and sensitizing insulin pathways of action are shown in Figure 5. Resistant dextrin reduces body weight and inflammatory biomarker levels by decreasing metabolic endotoxemia; at the same time, it inhibits phosphorylation of insulin receptor substrates through activation of amino-terminal kinases, which in turn regulates glycaemic status.

In summary, resistant dextrin regulates blood glucose through multiple pathways, including improving the sensitivity of terminal tissues to insulin and inhibiting sugar absorption and digestion. These findings provide a solid theoretical foundation and clinical basis for the application of resistant dextrin in diabetes treatment.

4.2. Fighting Overweight and Obesity. Overweight and obesity are important risk factors for cardiovascular disease, diabetes, certain cancers, and some other chronic diseases. At the same time, overweight and obesity can lead to a range of health and social and psychological problems. It is crucial to effectively curb overweight and obesity. In recent years, numerous studies have focussed on the application of resistant dextrin in the field of weight reduction and have found significant effects. A study by Hobden et al. [65] in an *in vitro* intestinal model confirmed that wheat starch-produced resistant dextrin significantly increased in key butyrate-producing bacteria Clostridium cluster XIVa and Roseburia genus in all vessels of the gut model. It also increased the production of short-chain fatty acids. These short-chain fatty acids effectively reduce body fat accumulation by altering energy metabolism, increasing oxygen consumption rate, and promoting fat thermogenesis and oxidation [66]. Resistant dextrin promotes fermentation by intestinal microorganisms in the large intestine to produce short-chain fatty acids, mainly acetic and propionic acids [8]. Animal model experiments have further elucidated the mechanism of action of short-chain fatty acids in weight management. This includes the activation of free fatty acid receptors and the induction of anorexigenic hormone release, which inhibits adipocyte synthesis [67]. In addition, studies have shown that 12 weeks of supplementation with resistant dextrin can improve obesity by reducing food intake and increasing metabolism [68]. These effects are due to the good water solubility and high water-holding capacity of the resistant dextrin, which produces a strong feeling of satiety after ingestion [69]. Resistant dextrin demonstrated increased satiety, suppressed energy intake, and reduced body weight in studies of both healthy adults in overweight Chinese men [70].

In summary, the main reasons for the improvement of body weight by resistant dextrin are as follows: firstly, it promotes the fermentation of intestinal microorganisms to produce more beneficial short-chain fatty acids; secondly, it increases the feeling of satiety and reduces food intake. These findings provide strong support for the application of resistant dextrin in the field of obesity suppression.

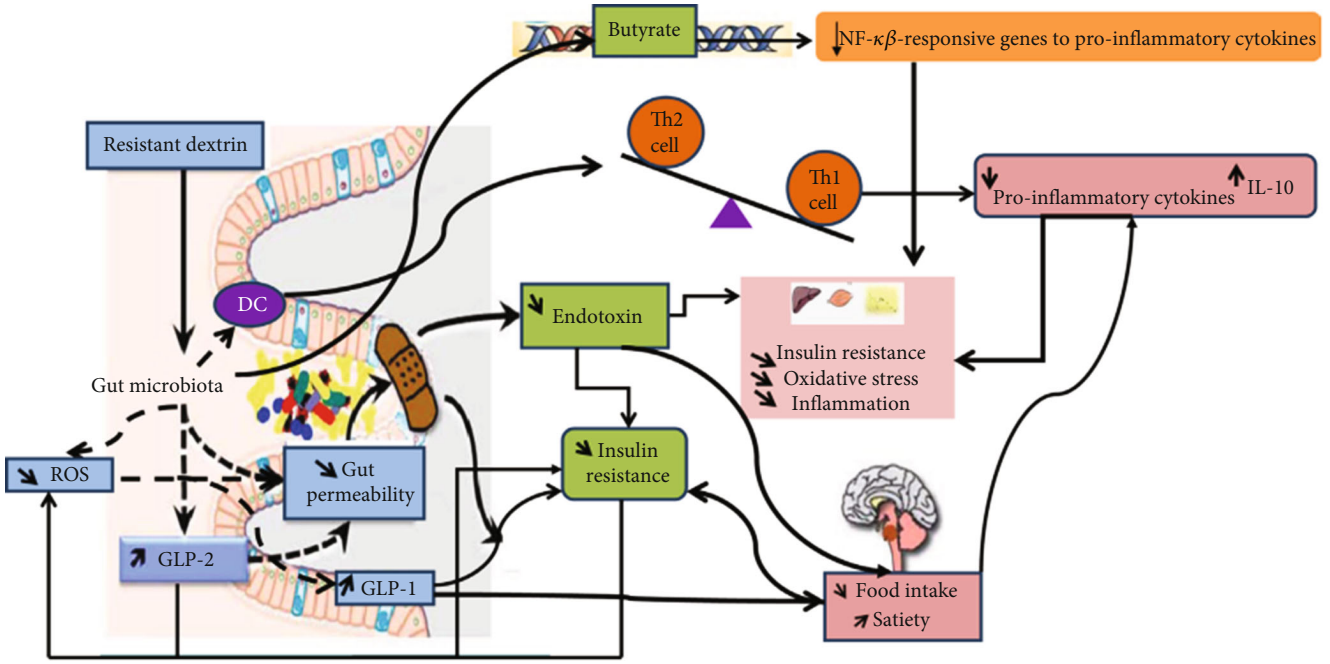

Figure 5: Probable mechanisms of the effect of resistant dextrin on inflammation and insulin resistance. Th: T helper; DC: dendritic cells; ROS: reactive oxygen species; GLP: glucagon-like peptide [11].

4.3. Improving the Intestinal Environment. When resistant dextrin is ingested by the human body, about 75% of it is fermented in the colon, while only a small amount is digested and absorbed in the small intestine. This property gives it a high potential comparable to prebiotics [71]. Compared to other oligosaccharides, resistant dextrin exhibits better tolerance in the human body and does not cause any digestive discomfort in the recommended dose range (40 g/d). However, higher daily doses (60 and 80 g) may cause flatulence but not diarrhea [72]. Furthermore, resistant dextrin selectively stimulates the growth of bifidobacteria and other short-chain fatty acid-producing bacteria in the large intestine. This effectively lowers the intestinal pH, resulting in an increase in the population of beneficial microorganisms and the suppression of harmful microorganism reproduction. Consequently, it creates a more favorable environment for the beneficial microorganisms residing in the intestine [73]. Hobden et al. [8] further confirmed that the inclusion of resistant dextrin modulates gut microbiota, altering the composition and activity of the intestinal flora. Additionally, the ingestion of resistant dextrin promotes the production of short-chain fatty acids, elevates the concentration of alpha-glucosidase in feces, enhances short-term satiety, and favors the growth of health-associated bacteria (e.g., Clostridium anomalum). It also inhibits the population of Clostridium spp. These findings provide compelling evidence for the utilization of resistant dextrin in promoting gut health [71, 74, 75].

5. Application of Resistant Dextrin

Since resistant dextrin was introduced, it has been widely used in the food industry and other fields. Currently, resistant dextrin is extensively utilized to create products with low calories, such as baked goods, dairy, and meat products. Additionally, it has also inspired the development of healthcare products and pharmaceuticals. Figure 6 shows the diverse applications and roles of resistant dextrin in different fields.

5.1. Application of Resistant Dextrin in Dairy Product. Resistant dextrin serves as a partial sucrose substitute in dairy products, effectively reducing their sugar content. Moreover, it has been observed to augment the biological activity of fermenting strains during yogurt fermentation, leading to significantly higher fermentation efficiency [76]. In a study by Renata et al. [77], it was demonstrated that incorporating resistant dextrin into lactose-free milk positively impacted the intestinal microbiota of individuals with lactose intolerance. Chen et al. [78] utilized milk powder as the main ingredient and successfully produced coagulated yogurt by incorporating 6% to 20% resistant dextrin. This addition not only resulted in favorable sensory evaluation and the desired level of acidity required for yogurt but also improved the product's nutritional value. However, it is crucial to control the amount of resistant dextrin added, as too little may result in poor results that do not appeal to consumers, while an excessive amount can negatively impact the product's sensory quality, leading to changes in taste and color.

5.2. Application of Resistant Dextrin in Flour Product. Incorporating resistant dextrin into pasta products represents a favorable approach for enhancing dietary fiber intake in daily diets. However, numerous studies have shown that adding dietary fiber inevitably affects the processing quality of flour products. Therefore, research exploring the impact of dietary fiber on the processing quality of wheat flour has

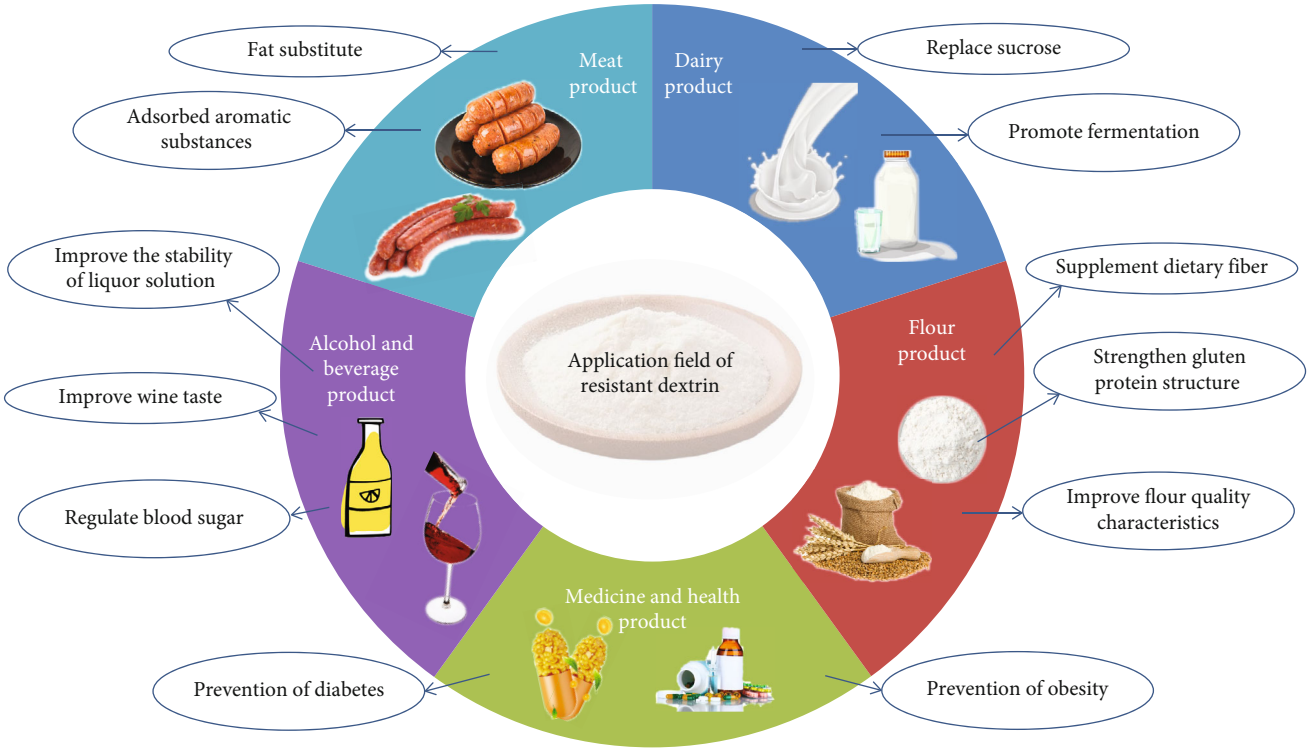

Figure 6: Application and role of resistant dextrin in various fields.

garnered significant attention in recent years within the field of cereal science [30, 79–81]. When dextrin-type fibers are used, the rheological behavior of dough, spreadability during baking, and penetration resistance are similar to those when sucrose is added, as resistant dextrin can exhibit plasticizing effects similar to sucrose, compared to inulin-type dietary fibers [82]. Yu et al. [1] added resistant dextrin to the dough, and not only could GI cookies with higher dietary fiber content be obtained, but the introduction of resistant dextrin would not affect the palatability of cookies. It can be seen that the addition of resistant dextrin to flour can lead to the production of products with a good texture and a high content of dietary fiber. In the future, consideration could be given to improving the nutritional value of the product without compromising its palatability, which could be a means of combating pandemic obesity and diabetes.

5.3. Application of Resistant Dextrin in Meat Product. The research scope of resistant dextrin application in meat products is extensive. Meat products inherently contain high fat and cholesterol levels, which can lead to complications like hypertension and coronary heart disease with excessive intake. Resistant dextrin can act as a partial fat substitute to reduce the presence of fat in the products without compromising taste and flavor. This facilitates the development of low-calorie meat products rich in dietary fiber. Furthermore, it can be utilized as a food additive to enhance taste and add commercial value [83, 84]. Schmiele et al. [85] replaced a portion of pork fat (0-20 g/100 g) with amorphous fiber (0-1.5 g/100 g) and compared the resultant model with a standard sample, assessing various sensory characteristics. This approach yielded a mock sample that closely resembled the standard one. Although certain sensory aspects of the simulated samples, such as shape and color, met the standard criteria, improvements can be made regarding the sensory characteristics of the fat substitutes. Currently, the application of resistant dextrin in meat products is limited, and its underlying mechanism of action remains incompletely understood. Future research directions should explore the physiological activity of resistant dextrin in meat products and investigate its interaction with common additives and seasonings used in meat products, such as soy protein and salts. This will provide valuable insights for its application in the meat industry.

5.4. Application of Resistant Dextrin in Wine and Beverage Product. Resistant dextrin can significantly decrease the surface tension of dissolved substances, thereby modifying the sensory characteristics of rice wine and red wine and improving their taste and stability [86]. According to Mateo-Gallego et al. [87], incorporating resistant dextrin into nonalcoholic beer resulted in improved glycemic control in overweight or obese individuals with diabetes compared to conventional nonalcoholic beer. The study showed a reduction of up to 18% in blood glucose levels in the subjects' plasma. In addition, the consumption of experimental nonalcoholic beer led to an 11.1% decrease in insulin concentration and a 1.92% decrease in insulin resistance index (HOMA-IR), indicating a synergistic effect on overall metabolism, particularly in glucose regulation. Resistant dextrin, with its slightly sweet taste and low caloric properties, is also utilized in producing sugar-free functional beverages. Major companies like

Coca-Cola, Nestle, Danone, and China Mengniu Dairy have already incorporated resistant dextrin as a water-soluble dietary fiber in their products, such as Coca-Cola's dietary fiber cola and China Mengniu Dairy's light milkshake milk [88].

5.5. Other Applications of Resistant Dextrin and Future Application Trends. Hasan et al. [89] conducted an environmentally friendly green synthesis of polymethyl methacrylate-grafted nanosilver using dextrin as a raw material. The resulting biofilms exhibited over a 70% reduction in all tested pathogens, which was crucial for inhibiting MDR and provides new insights into the application of resistant dextrin in innovative fields. Compared to other prebiotic fibers and oligofructose, resistant dextrin is considered the most effective drying aid, especially in the spray drying of pomegranate juice concentrates [90]. It can also be used as a replacement for maltodextrin in various fruit juices, leading to the development of prebiotic powders that can be utilized to create novel functional foods. Additionally, the unique molecular structure of resistant dextrin makes it an ideal filler excipient for the production of whole powder pressed tablets. This offers new materials for structural innovation in pharmaceuticals and health products.

6. Conclusions and Future Outlook

Resistant dextrin, a novel starch-based dietary fiber, has emerged as a pivotal auxiliary ingredient in food processing. Various processing methods and conditions, including acid type, heat treatment duration, and physical and chemical modifications, can significantly influence the *in vitro* digestibility of resistant dextrin. The produced resistant dextrin exhibits unique physicochemical properties, including high solubility, excellent thermal stability, and a pronounced prebiotic effect, which endow it with tremendous potential for applications in the food industry. These properties are intimately linked to the molecular structural features of resistant dextrin, such as glycosidic bond conformation, chain length distribution, and molecular weight. Furthermore, numerous studies have underscored the positive impacts of resistant dextrin on lowering blood glucose, reducing body weight, enhancing insulin sensitivity, and improving satiety in both animal and human models.

However, despite the milestones achieved in the research of resistant dextrin, many challenges remain:

(1) Product purity and quality assurance: the efficacy of resistant dextrin in foodstuffs varies considerably depending on its purity. In practical production processes, the purification of certain products remains inadequate, and the presence of impurities can compromise the efficacy of resistant dextrin. Although numerous separation and purification methods have been proposed, their practical application is constrained by various factors, posing challenges for large-scale production. Consequently, the development of efficient purification techniques suitable for large-scale production has become a pressing priority

(2) Insufficiently in-depth molecular structure studies: current research focuses on the optimization of production processes for resistant dextrin, the exploration of health mechanisms, and their application in food. However, in-depth studies on the relationship between its molecular structure and its properties are still insufficient

(3) Untapped potential effects: resistant dextrin may have additional undiscovered physiological effects, such as their role in the regulation of intestinal flora, metabolite effects, immune responses, and ulcerative colitis. Future studies could explore the potential of resistant dextrin to improve glucose tolerance and metabolic stability by regulating the intestinal flora with the help of advanced methods such as faecal microbiota transplantation

In summary, resistant dextrin faces many challenges while showing great application prospects. Solving these problems will further promote the wide application of resistant dextrin and release its greater market value.

Consent

The authors declare their consent to publish this article.

Conflicts of Interest

The authors declare no conflict of interest relevant to this article.

Authors' Contributions

Conceptualization was managed by X.W. and J.Z.; methodology was managed by X.Y. and X.W.; visualization was managed by Q. Z and M.L. All authors have read and agreed to the published version of the manuscript. Xiuli Wu and Jianwen Zhang contributed equally to this work.

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