Chapter 2
Slowly Digestible Starch

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2.1 Introduction

Starch is the main carbohydrate in human nutrition and is probably the second most abundant natural biopolymer on earth after cellulose. It is a major component of staple foods and plays important roles in bodily health by helping to maintain proper metabolic energy levels. Based on the rate and extent of its digestibility, starch has been classified into rapidly digestible starch (RDS), slowly digestible starch (SDS), and resistant starch (RS). The starch fraction digested within 20 min of incubation is classified as RDS; the starch fraction digested within 20–120 min corresponds to SDS; and the remaining fraction, which is not digested further, is RS (Fig. 2.1a) [1–3].

RDS induces a fast increase in blood glucose and insulin levels, which may cause a series of health complications, such as diabetes and cardiovascular diseases. SDS is slowly digested throughout the small intestine, resulting in the slow and prolonged release of glucose into the bloodstream, coupled to a low glycemic response. This type of starch may be helpful in controlling and preventing hyperglycemia-related diseases. RS is a type of starch that cannot be digested in the small intestine (Fig. 2.1b) [3].

The accurate determination of the bioavailable carbohydrates in a given product allows the manufacturer to predict and communicate the glycemic response to each serving of the food, which is especially important for therapeutic foods consumed by diabetics, and the management of diabetes and disorders of carbohydrate metabolism. The concept of the glycemic index (GI) was introduced to classify foods on the basis of the postprandial blood glucose response they induce. GI is defined as the postprandial increment in the glycemic area under the glycemic dose–response

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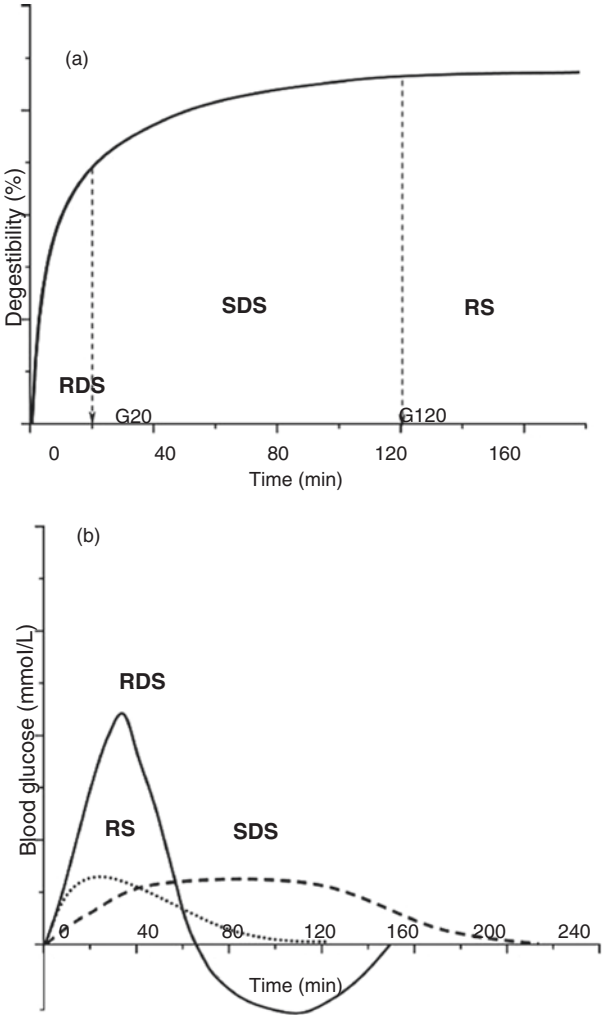

Fig. 2.1 Classification of the bioavailability of nutritional starch fractions. (**a**) In vitro digestion and (**b**) in vivo glycemic responses to RDS, SDS, and RS [3]. *RDS* rapidly digestible starch, *SDS* slowly digestible starch, *RS* resistant starch

curve after a test meal, expressed as a percentage of the corresponding area after an equi-carbohydrate portion of a reference food, such as glucose or white bread [4, 5]. Several researchers have demonstrated a strong relationship between the rate of in vitro digestion and the glycemic response to food. Such studies can be used to identify foods with potential utility in the diets of individuals with diabetes.

The digestibility of starch is determined by several factors. The important factors are the starch characteristics, the physical access of enzymes to the starch, the

availability of the water required for the hydrolysis of glycosidic linkages, and the rate of diffusion and the viscosity of the substrate.

The plant source of starch affects its digestibility. The digestibility of cereal starches, such as wheat starch, barley starch, oat starch, cornstarch, and sorghum starch, decreases in that order, and the digestibility of legume starch is lower than that of cereal starches [6]. The granule size of a starch is directly related to its digestibility, and studies of debranched cooked rice starch have shown that larger granules reduce the rate of digestion.

On the basis of X-ray diffraction scattering studies, native starch is classified into A, B, C, and V types. The crystallization of the starch granule structure also affects starch digestibility. X-ray diffraction scattering studies of three different starches (cereal starch, tuber starch, and bean starch) showed that cereal starch has a type A pattern, and its digestion rate is highest; tuber starch, such as potato starch, has a type B pattern, and its digestion rate is lowest; and bean starch has a type C pattern, and its digestion rate is between those of cereal starch and tuber starch [7].

Obesity and diabetes have become major public health concerns worldwide, and the number of cases has increased exponentially in recent years. New discoveries in food and nutrition science imply that slowing the rate of digestion of the glucose derived from ingested carbohydrate sources blunts glycemia, reduces the insulin required, and induces satiety [6]. Some examples of commercially available products that slow the rate of glucose digestion include isomaltulose, trehalose, pullulan, and sucromalt, together with other slow-release energy beverages, fodders, and medicines [8]. All these products claim to slow and extend the postprandial level of glucose after intake, although they differ in their molecular structures, functional properties, and potential applications in conjunction with SDS.

SDS food products are currently very limited in food markets [1, 9, 10]. However, a new slow-digesting rice starch (Ricemic), developed by the US Department of Agriculture (USDA), and a kind of starch-based cereal food, EDP® (“energy delivered progressively”), are available in markets [11]. This chapter focuses on the preparation, structures, physicochemical properties, functions, and potential applications of SDS.

2.2 Preparation of SDS

Native starch is a good texture stabilizer and regulator of food systems, but factors such as its low shear resistance, thermal resistance, and high tendency to retrogradation restrict its use in some food applications. Starch is commonly modified both chemically and physically to generate starches with special functional properties. However, most industries (especially the food and pharmaceutical industries) prefer starches that have been physically altered, to ensure their relative safety. SDS can also be prepared with enzymatic methods or several of these methods.

2.2.1 Physical Modification Methods

The advantages of using physical methods to prepare SDS are that these methods are considered more natural and are very safe [12]. The physical modification methods used to produce SDS include hydrothermal, malleablization, autoclaving, microwaving, and polymer entrapment methods (Table 2.1) [13–20]. The SDS content of pea starch is the highest of the native starches. Heat–moisture treatment (HMT) markedly improves the SDS content of waxy potato, potato, waxy corn, rice, yam, and banana starches, whereas it has little obvious effect on pea starch.

A higher percentage of SDS is mainly attributed to the facts that intact starch granules are retained during physical modification treatments and that intact granules are less susceptible to amylolytic enzymes. Some treatments cause the formation of amylose–lipid complexes in the starch granules, which can lower the susceptibility of SDS products to enzymatic degradation. In other words, any physical modification of the starch structure that affects enzyme binding and therefore the rate of its digestion can be used to modulate starch digestibility and form SDS [18].

On the other hand, a higher percentage of SDS can involve a higher ratio of imperfect crystallites to perfect crystallites. Most SDSs consist of amorphous regions and weak crystallites, with a high proportion of dextrin, with a degree of polymerization (DP) ≥ 25. This structural information can be used to develop low-digestibility food products.

Table 2.1 Physical modification methods for preparing SDS

Modified method	Native starch	Preparation condition	Content of SDS/%		References
			Native starch	Modified starch	
HMT	Waxy potato	Water 25.7%, 120 °C, 5.3 h	8.1	41.8	[13]
HMT	Pea	Water 30%, 120 °C, 24 h	40.3	45.3	[14]
HMT	Potato	Water 30%, 30 °C, 12 h	5.4	37.5	[15]
HMT	Waxy corn	Water 35%, 120 °C, 10 h	0.8	9.3	[16]
HMT	Germinated brown rice	Water 30%, 100 °C, 1 h	39.1	46.3	[17]
HMT	Rice	Water 16%, 121 °C, 1 h	38.2	43.3	[18]
Malleableize	Pea	Water 70%, 50 °C, 24 h	40.3	43.2	[14]
Autoclaving	Yam	Water 83%, 121 °C, 1 h	15.0	34.1	[19]
Parboiling	Corn	Water 83%, 60 °C water bath 2 h	22.2	35.5	[19]
Microwave	Banana	Water 83%, 20 min	9.9	18.3	[19]
β-Cyclodextrin	Rice	Water 80%, 25 °C, *β*-CD 3%	18.1	52.1	[20]

HMT heat–moisture treatment

Figure 2.2 [13] shows the surface features and cross-sectional views of HMT waxy potato starch granules. Scanning electron micrographs of the native starch granules show round or oval shapes, with no evidence of fissures or cracks (Fig. 2.2a1), and the cross sections show no hollow internal structures (Fig. 2.2a2). However, the surfaces of all the HMT samples show signs of cracking and dents (Fig. 2.2b1–f1), and the cross section of each starch granule shows a large hollow in

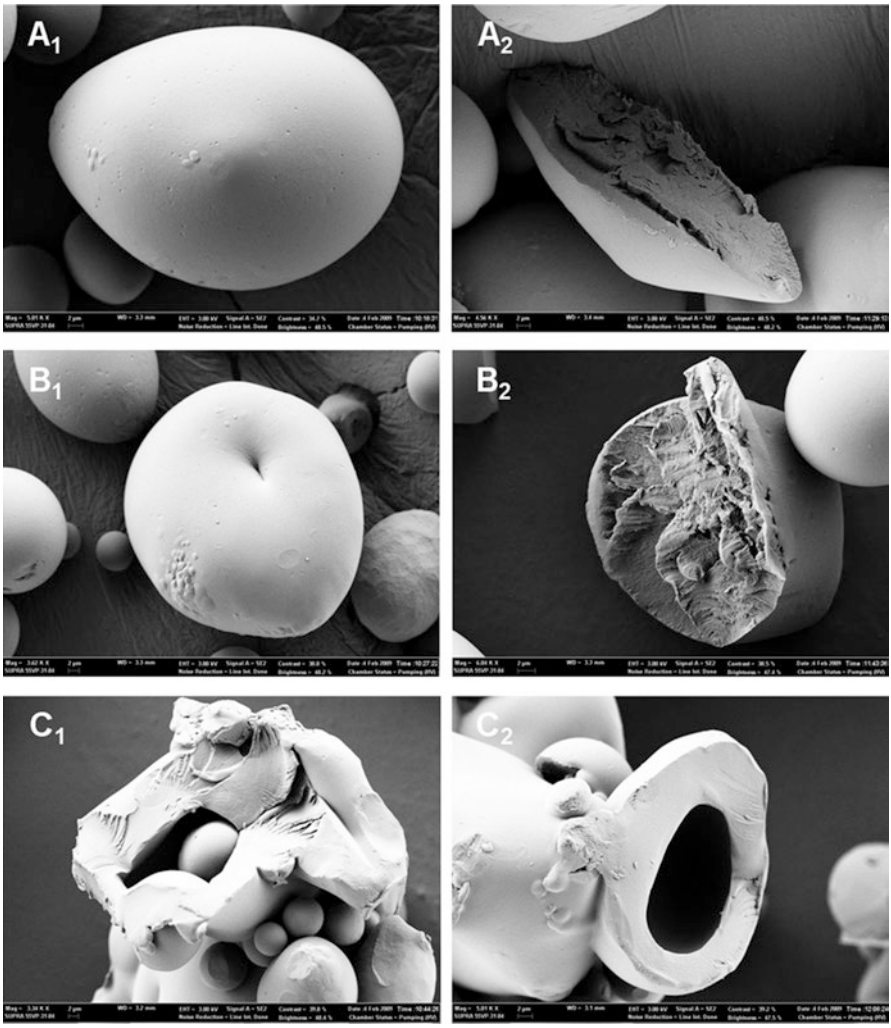

Fig. 2.2 Scanning electron micrographs of heat–moisture-treated (HMT) waxy potato starch: (**a**) native starch; (**b**) sample B (20%, 110 °C, 5 h); (**c**) sample C (30%, 130 °C, 1 h); (**d**) sample D (20%, 130 °C, 9 h); (**e**) sample E (30%, 150 °C, 5 h); (**f**) sample F (25.7%, 120 °C, 5.3 h). (1) SEM images of the surfaces of the starch granules; (2) SEM images of the cross section of the starch granules [13]

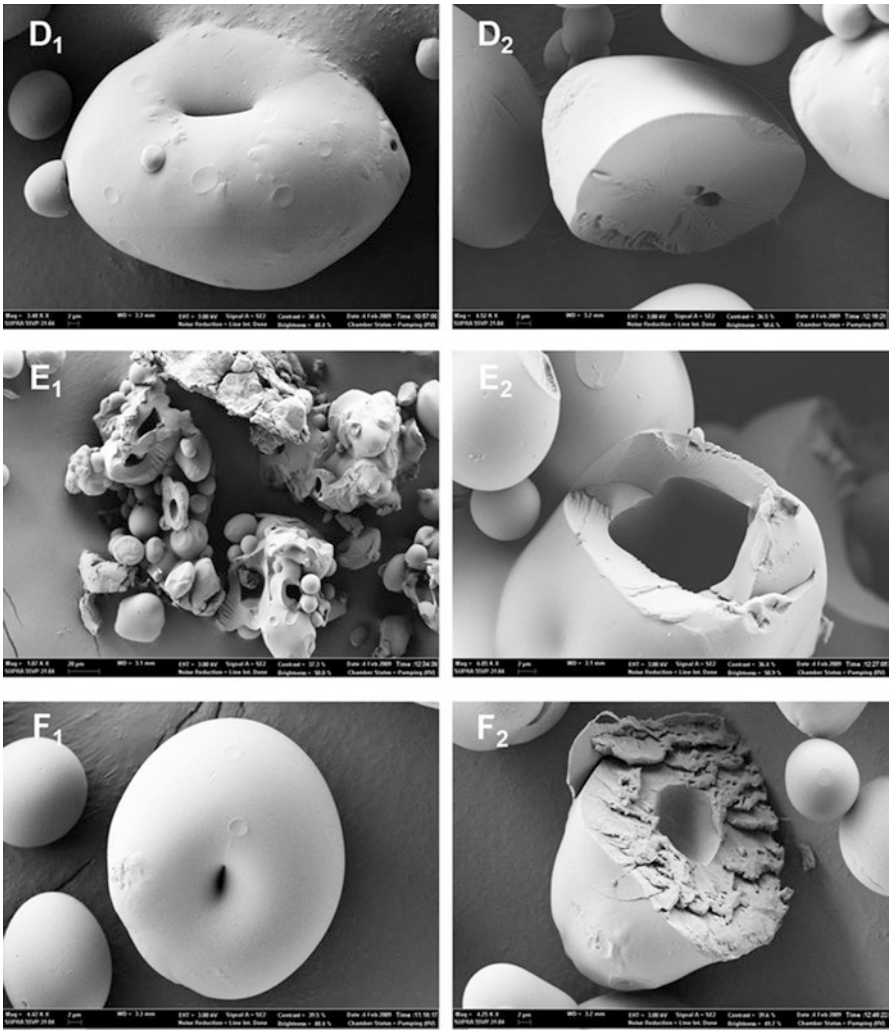

Fig. 2.2 (continued)

the central region, the size of which is probably proportional to the moisture level. These results may be attributable to the partial swelling and disruption of the starch granules by the abundant water molecules. The hollow structures at the centers of the HMT starch granules may have resulted from the rearrangement of the molecular structure and the disintegration of the central tissue during HMT. At a high moisture level (30%), the hollow region was large and readily visible.

Both samples B and D were treated with 20% moisture. No hollow region was observed in the cross section of starch sample B (110 °C, 5 h), but a small hollow region was observed in sample D (130 °C, 9 h). Therefore, this difference is attributable to the higher treatment temperature and longer treatment time. Samples C

(130 °C, 1 h) and E (150 °C, 5 h) were both treated with 30% moisture and showed the largest hollow regions. Overall, the size of the hollow region increased as the moisture level, temperature, and time of treatment increased. Among these three factors, the moisture level had the most significant effect on the size of the hollow region [13].

The development of new crystallites in the amorphous region through the interactions between amylose chains or the formation of crystalline amylose–lipid complexes may contribute to the reduction in enzyme sensitivity of HMT starches [16]. Recent studies have demonstrated that the hydrophobic section of some lipids is preferentially introduced into the central axis of the amylose helix to form an amylose–lipid complex during interactions between amylose and lipids [21, 22]. The amylose chain of starch has a natural twist, producing a helical conformation with six anhydroglucose units per turn [7]. Amylose has a helical conformation and can form inclusion complexes with small hydrophobic molecules. Complexes between fatty acids, such as lauric acid, and amylose can form rapidly under physiological conditions and contribute to the formation of both SDS and RS [23]. The formation of such complexes with lipids can cause significant changes in the behavior of starch, reducing its solubility, increasing its gelatinization temperature, delaying its retrogradation, and increasing its resistance to digestive enzymes.

The complex formed has an unstable V-type crystalline structure and inhibits the formation of B-type recrystallized starch. The stability of the V-type complex to amylolytic and lipolytic enzymes has been estimated, and its melting temperature is above 100 °C [22]. This resistance to high temperature protects SDS from dissociation during food processing. However, the lipid content added during the formation of amylose–lipid complexes often exceeds 10% and contributes a lot of additional energy.

Zhan et al. demonstrated that β-cyclodextrin (β-CD) interacts with paddy starch to increase the yield of SDS. Under the optimum conditions for modification (β-CD, 3%; water, 80%; and equilibrium temperature, 25 °C), the maximum SDS yield was 52.1%. The basic rule for conferring slow digestibility is the formation of starch–β-CD non-inclusion complexes with a partial V-type structure and weak resistance to enzymes. Starch–β-CD non-inclusion complexes were found more suitable for improving the SDS yield than starch–lipid complexes [20]. In vivo data have suggested that potato amylose–lipid complexes (weight ratio, amylose/lipid = 5:1, 60 °C) are hydrolyzed and absorbed within 120 min of ingestion to the same extent, but somewhat more slowly, than uncomplexed starch, with a 12% lower digestion rate [24].

Figure 2.3 [25] presents SEM images of a rice SDS product prepared with single-retrogradation or dual-retrogradation treatments over different time intervals. In that study, rice starch (5.0 g) was dispersed with two volumes of distilled water and heated in a boiling water bath for 30 min. The resultant gel was hermetically sealed and stored at 4 °C for 24, 36, or 48 h to analyze its retrogradation. The retrograded samples were regelatinized in a boiling water bath for 20 min and subjected to a dual-retrogradation treatment for periods of 24, 36, and 48 h. Each of the resulting gels was dried at 40 °C for 8 h. The SEM images revealed that the SDS products that

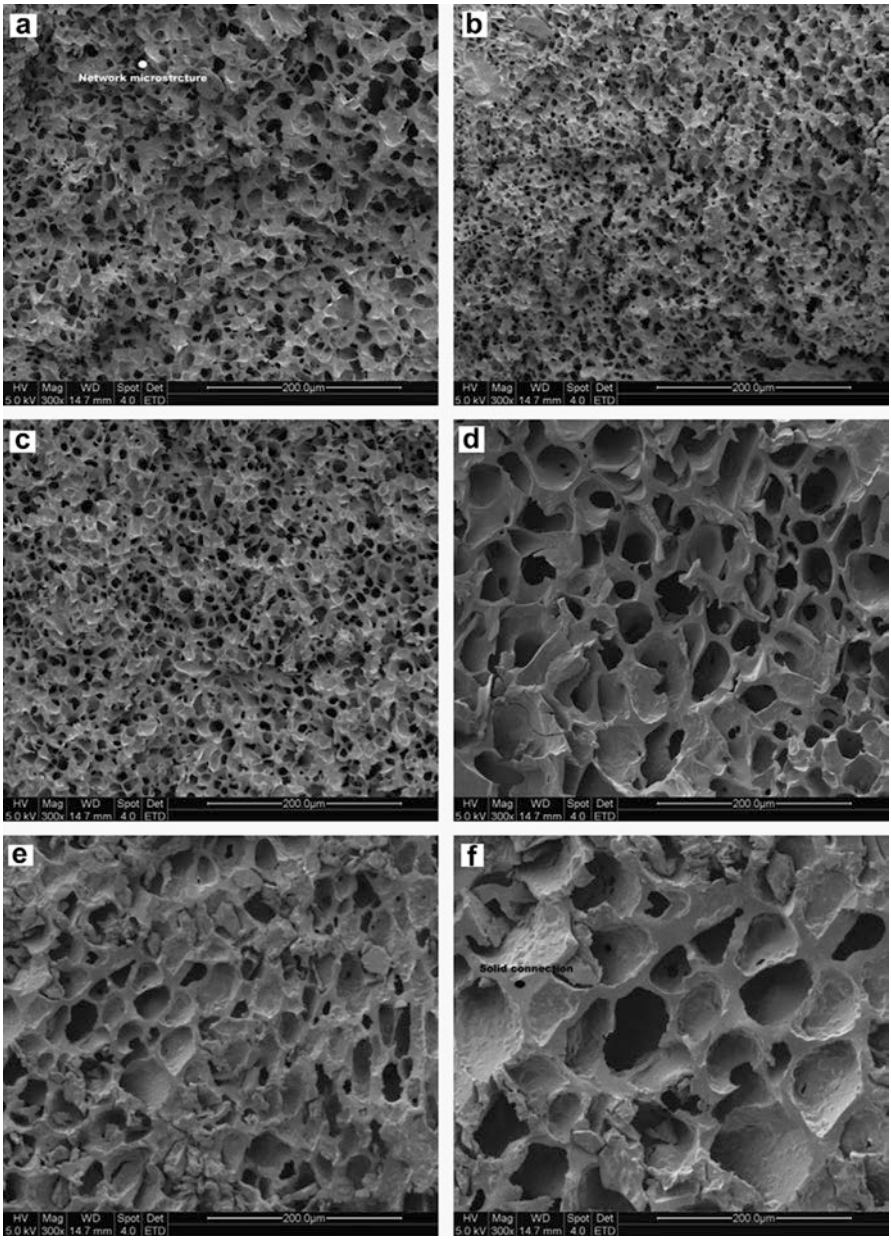

Fig. 2.3 Scanning electron micrographs of SDS products prepared from rice starch by (**a**) single retrogradation with a time interval of 24 h, (**b**) single retrogradation with a time interval of 36 h, (**c**) single retrogradation with a time interval of 48 h, (**d**) dual retrogradation with a time interval of 24 h, (**e**) dual retrogradation with a time interval of 36 h, and (**f**) dual retrogradation with a time interval of 48 h [25]

underwent single retrogradation had network microstructures with smaller cavities than those observed in SDS after dual retrogradation. This morphological conformation was produced by starch gelatinization, but was not affected by the retrogradation time (Fig. 2.3a, e, c). However, larger holes and more solid connecting parts were observed in the SDS products subjected to dual retrogradation (Fig. 2.3). The larger cavities reduced the contact area between the starch and amylase molecules. Furthermore, the solid connecting parts formed during the dual-retrogradation treatment prevented the starch molecules leaching out and produced moderate retrogradation, resulting in a higher SDS yield. Compared with single retrogradation, dual retrogradation generated larger cavities and more solid connection parts in the SDS products. This internal microstructure increased the degree of slow digestibility. These findings suggest that dual retrogradation can be used to increase the yield of SDS in starchy products.

2.2.2 Chemical Modification Methods

Starches are modified by chemical methods to improve their functionality and increase their commercial value. Several key structural properties of starches can be modified to functionalize the copolymer to meet specific requirements and to confer a variety of physicochemical benefits.

Many modified starches made for food use contain only small amounts of substituent groups and are used as safe food ingredients. Legislative approval for the use of novel starch derivatives in processed food formulations is still under debate, but several tailor-made starch derivatives with multiple modifications are being prepared and characterized [7]. Some chemically modified starches are increasingly used as fat replacements or fat substitutes in different food systems. These starches are either partially or totally undigested and therefore contribute few calories to the food [7].

The chemical modification of starch is generally achieved through its derivatization, including the etherification, cross-linking, oxidation, substitution, and grafting of the starch molecule. Chemical modification involves the introduction of functional groups into the starch molecule, which markedly alters its functional properties. These modifications of native granular starches profoundly alter their gelatinization, pasting, and retrogradation behaviors [26].

Some chemical methods used to prepare SDS are shown in Table 2.2 [19, 27–29]. After treatment with acid or esterification, the SDS content of the modified starch is significantly greater than that of the native starch.

Chemical reagents provide nonionic, cationic, hydrophobic, or covalently reactive substituent groups. These modifications generally alter the gelatinization and pasting properties of starch [30]. Citric acid, a polyfunctional carboxylic acid, can be used to esterify the hydroxyl groups on starch, resulting in the formation of cross-links and improving the starch properties or SDS content [27].

Table 2.2 Chemical modification methods for preparing SDS

Reagents	Native starch	Preparation condition	Content of SDS/%		References
			Native starch	Modified starch	
Citric acid	Paddy rice	2.62 mmol acid/20 g starch, 128.4 °C, 13.8 h	9.8	23.0	[27]
Citric acid	Mung bean	Citric acid 30%, starch 20%, pH 2.0, 120 °C, 1 h	15.1	23.3	[19]
Hydrochloric	Mung bean	Hydrochloric 1.0 mol/L, starch 20%, pH 5.0, 120 °C, 1 h	15.1	23.3	[19]
Vitriol	Mung bean	Vitriol 0.3 mol/L, starch 20%, pH 2.0, 120 °C, 1 h	15.1	23.3	[19]
OSA	Waxy corn	OSA 3%, starch 40%, pH 8.4, 35 °C, 2.3 h	15.0	25.0	[28]
OSA	Waxy corn	OSA 3%, starch 57%, pH 8.5, 20 °C, 6 h	15.3	28.1	[29]

OSA octenyl succinic anhydride

A study of paddy rice starch treated with citric acid (2.62 mmol acid/20 g starch, 128.4 °C for 13.8 h) showed an increase in the apparent amylose content from 21.1% to 30.3%, indicating that it contained more linear chains, derived from the amylopectin side chains and acid-hydrolyzed amylose. The reduced molecular weight caused by the acid treatment allowed a greater freedom of polymer motion and enhanced its ability to form more stable structures that better resisted enzymatic hydrolysis [27].

Esterification with octenyl succinic anhydride (OSA) is one of the modifications that most effectively increase SDS. OSA-modified starch showed an extremely low glycemic response during human trials, consistent with the extended glucose release profile of SDS [28]. The SDS (42.8%) produced by subjecting OSA-treated waxy corn starch to HMT (10% moisture, 120 °C for 4 h) was higher than that produced by treating OSA-modified starch with the Englyst test method (28.3%). The modified starch products with attached OSA molecules may act as noncompetitive inhibitors of digestive enzymes, reducing enzyme activity and thereby slowing digestion [28, 29]. As these studies show, chemical modification can be used to prepare SDS, but clinical and toxicological trials are required to evaluate the safety and nutritional efficacy of consuming this SDS.

2.2.3 Enzymatic Modification Methods

The enzymatic processing of starch is a commonly used and effective modification technique. Enzymatic treatments of starch with pullulanase, isoamylase, α-amylase, β-amylase, or transglucosidase can change the chain lengths of starch, thus achieving the appropriate digestibility and glycemic response [31, 32].

After treatment with different kinds of enzymes, the structures and physicochemical properties of starches change. Some enzymatic methods used to prepare SDS are shown in Table 2.3 [33–35]. After treatment with enzymes, the SDS contents of most starches clearly increase. After treatment with pullulanase, the SDS content of native waxy rice starch reached a high level but decreased to 24.9% after cooking [33].

Xiong studied the SDS content of normal corn starch after *β*-amylase, transglucosidase, or maltogenic amylase treatment. The product obtained after processing with *β*-amylase showed an increased SDS content, with an average chain length of DP 16.16 and a branch density of 6.19%. After treatment with a combination of enzymes (*β*-amylase and transglucosidase), the product had a higher SDS content, with an average chain length of DP 14.36 and a branch density of 6.96%. After treatment with maltogenic amylase, the product had the highest SDS content, with an average chain length of DP 10.95 and a branch density of 9.13%. These results sug-

Table 2.3 Enzymatic modification methods for preparing SDS

Enzymes	Native starch	Preparation condition	Content of SDS/%		References
			Native starch	Modified starch	
Pullulanase	Waxy rice	Starch (10% w/v) boiled with continuous stirred for 30 min, adjust temperature to 58 °C, pullulanase 60 ASPU/g, 12 h	45.5	57.8	[33]
Amylosucrase	Waxy rice	Starch (2%, w/w) and sucrose (100 mM) in 100 mM in sodium citrate buffer (pH 6.0), boil suspension for 10 min. Adjust temperature to 30 °C, add amylosucrase (40,000 U), 40 h	4.9	29.1	[34]
Amylosucrase	Waxy corn	Ditto	5.2	30.2	[34]
Amylosucrase	Waxy potato	Ditto	4.4	24.2	[34]
β-Amylase	Normal corn	Starch (8% w/v) shake for 20 min in 95 °C, adjust temperature 55 °C, pH 5.2, adding 0.032% *β*-amylase, shake for 12 h	15.2	22.4	[35]
β-Amylase+ transglucosidase	Normal corn	Starch (8% w/v) shake for 20 min in 95 °C, adjust temperature 57 °C, pH 5.2, adding mixed enzyme (composited ratio, 0.032%:8 TGU), shake for 8 h	15.2	33.5	[35]
Maltogenic amylase	Normal corn	Starch (8% w/v) shake for 20 min in 95 °C, adjust temperature 60 °C, pH 4.8, adding 40 mg/kg maltogenic amylase shake 16 h	15.2	38.1	[35]

ASPU enzyme activity, *TGU* enzyme activity

gest that enzymatic treatments can increase SDS contents and that treatment with maltogenic amylase is most effective [35].

The molecular weight of most starches decreases rapidly during enzymatic treatment. According to BeMiller and Whistler, a native starch formed two fractions with different molecular weight: amylopectin, which is a larger molecule (10^7–10^8), and amylose, which is a smaller molecule (10^4–10^6) [36].

The addition of enzymes reduced the contents and molecule weights of both amylose and amylopectin. According to Christophersen, maltogenic α-amylase quickly reduced the peak DP of amylose, with the formation of only minor glucose, maltose, and other low-molecular-weight oligosaccharides. They reported that only 3% of other low-molecular-weight oligosaccharides were produced, but the DP was dramatically reduced from DP 350 to DP 123 [37]. Bijttebier et al. reported that the maltogenic α-amylase from *Bacillus stearothermophilus* preferentially hydrolyzed the exterior chains of amylopectin during the early stages of hydrolysis but also hydrolyzed the inner chains, with high multiple attack action, during the later stages [38]. These data suggest that the endomechanism of maltogenic α-amylase is consistent with the reduced molecular weight of the starch molecule. It is generally known that amylopectin consists of multiple clusters connected by long linear chains. Based on the enzymatic properties of the branching enzyme, the α-1,6-linked segments between the amylopectin clusters are hydrolyzed to release the cluster units. Similar findings have been reported by the others [39]. The action of enzymes on the linear chain of amylose can also form branched linkages and a cyclic amylose, and these reactions may change the physical structure of the substrate, slowing its digestion time [40, 41].

According to the Hizukuri cluster model, amylopectin molecules have A, B (B1–B4), and C chains, and the fractions DP < 13 and DP 13–30 together constitute the short chains, corresponding to the A + B1 chains. The other longer-chain fractions correspond to the B2–B4 chains [42]. It has been reported that maltogenic α-amylase has a marked effect on the side-chain distribution of starch and especially reduces the number of short B chains [43]. In that study, maltogenic α-amylase reduced the levels of the outer chains (primarily A and B1) by 50% compared with the control sample, with little effect on the internal chain length. Based on these observations, it can be concluded that the addition of maltogenic α-amylase reduced the molecular weight of amylopectin, and significantly affected the side-chain distribution of the residual amylopectin, increasing the relative numbers of short chains. The reduced proportion of short chains could lead to the formation of more perfect crystallites, increasing the starch's resistance to starch-digesting enzymes [43].

In the study by Miao et al., gelatinized cornstarch (10% w/v, pH 5.0) was treated with maltogenic α-amylase (5 U/g dry weight of starch, 55 °C). The product had a higher proportion of short chains than the native cornstarch (44.2% and 23.7%, respectively), which maximized the SDS content (19.6%) [44]. A starch debranching analysis (mutant cornstarch debranched with isoamylase) revealed a parabolic relationship between the SDS content and the weight ratio of amylopectin short chains (DP < 13) to long chains (DP > 13). Amylopectin with higher amounts of either short chains or long chains can contain relatively large amounts of SDS [45].

2.2.4 Composite Modification Methods

Compared with the modification methods discussed above, the composite modification methods have several advantages in the preparation of SDS, including greater efficiency and cost-effectiveness. Some composite modification methods used to prepare SDS are shown in Table 2.4 [46–50], including different combinations of physical, chemical, and enzymatic methods. The combination of different kinds of modification methods has several advantages, including a great increase in the SDS content compared with the native starch.

Dual modification methods combining debranching modification and other types of modification can be used to prepare SDS with various properties and functionalities. Debranched-acetylated starch and debranched-octenyl succinylated (OSA) starch have shown great potential utility in starch–lipid complexes, low-fat salad dressings, and emulsion stabilizers [51–53]. Recently, there has been increasing interest in the preparation of micro- and nanocomposites [54–57]. These new composites, with slow digestibility and barrier properties, can be used to design economic and biocompatible delivery systems for bioactive agents in foods, beverages, and pharmaceutical agents.

In general, the physical modification methods for SDS have several disadvantages, including lower yield. Moreover, the equipment required to produce SDS products is always expensive and cannot meet the requirements for continuous production. However, it is the safest way to generate SDS because no hazardous substances are incorporated into the products during processing. Chemical production methods for SDS are widely used in industry, but the use of chemical reagents in the production process is not environmentally friendly, and their application to food products is restricted. Enzymatic methods are suitable for producing many SDS products, but the cost is so high that they cannot meet the demands of industrial production. Together with the several other advantages of composite methods, the SDS produced with composite methods is more stable to heat than that produced by other methods.

2.3 Digestibility of SDS

An apparent direct negative relationship between large granules and starch digestibility was reported in 1922. Many studies have since confirmed this relationship [58]. Lindeboom reported that small barley and wheat starch granules are hydrolyzed faster than large granules [59]. Singh et al. observed significant differences between the enzymatic hydrolysis of different native potato starches when fractionated according to small, medium, and large granules [26].

The lower susceptibility of large granule starches to enzymatic hydrolysis has been attributed to the smaller specific surface area of the granules, which may reduce the extent of enzyme binding and ultimately result in less hydrolysis that occurs in small granules [60].

Table 2.4 Composite modification methods for preparing SDS

Modified method	Native starch	Preparation condition	Content of SDS/%		References
			Native starch	Modified starch	
Pullulanase – retrogradation	Waxy corn	Native starch samples hydrolyzing with pullulanase (20 U/g) for 6 h and then cooled at 4 °C for 2 days	–	45.1	[46]
Pullulanase – lipid	High amylose corn	Native starch slurry (10% w/v, pH 4.4) cooked in boiling water bath with stirring for 30 min. Adjusted temperature to 60 °C, add pullulanase 40 ASPU/g of starch for 2 h; mix with lauric acid (10% w/w, db), boiling water bath for 30 min	6.6	11.2	[47]
Emulsifier – alcohol	High amylose corn	Native starch 5 g, glycerin monostearate 0.5 g, 40% ethyl alcohol 35 mL, KOH (3 M) 25 mL cooked in 35 °C water bath for 15 min	–	67.4	[48]
Cross-link – esterification	Waxy rice	Native starch slurry (35% w/v, pH 9) with STMP 6.5% cooked in 35 °C water bath for 4.5 h; adjusted to pH 8, add OSA 5.3%, cooked for 15 h	13.8	33.8	[49]
Ultrasonic wave – pullulanase	Corn	Native starch slurry (10%) cooked in 70 °C water bath for 20 min; adjusted to 40 °C, add 14% pullulanase, ultrasonic wave (300 W) for 40 min	25.3	43.1	[50]
Microwave – HMT	Corn	Water 60%, 50 °C, microwave 300 W for 25 min	25.3	38.3	[50]

ASPU enzyme activity, *db* dry starch base, *HMT* heat–moisture treatment, *STMP* sodium trimetaphosphate, *OSA* octenyl succinic anhydride; "–" means not mentioned

How the structural aspects of SDS are related to the mechanisms of its digestion and their health implications have been investigated and reported [21, 61]. Based on current data, the slow digestibility of SDS is caused by two factors, its physical structure and chemical construction, both of which reduce the contact between enzymes and SDS.

2.3.1 Physical Structure of SDS and Its Digestibility

The digestion of starch granules is a complex process that includes different phases: the diffusion of the enzyme toward the substrate, which is affected by the porosity of the substrate; the adsorption of the enzyme to the starchy material; and the

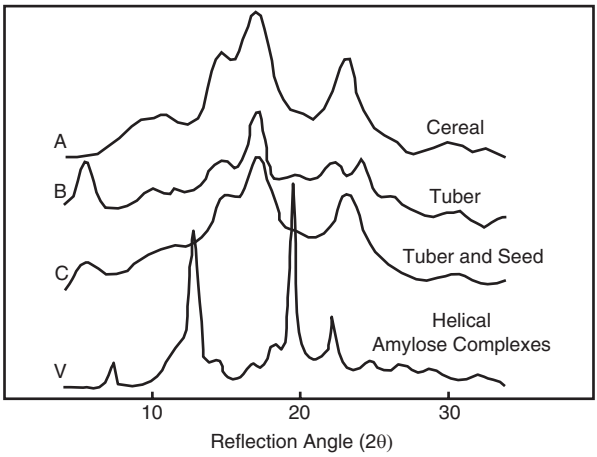

Fig. 2.4 X-ray diffraction patterns of different starches [7]. A, B, C, V: types of crystal structures in starch

hydrolytic event [62]. A large amount of starch is protected from the protein and other components of food, and is not contacted by digestive enzymes, which is why pasta contains so much SDS.

X-ray diffraction scattering studies have classified native starches into types A, B, C, and V (Fig. 2.4) [7]. The molecular structure of the starch granules, especially the arrangements in A-type and B-type crystallites, influences the hydrolysis of the starches. A-type polymers are less resistant to amylase hydrolysis than B-type polymers. The shorter double helices and interior crystallites present in A-type starches are more susceptible, whereas long chains form longer and more stable helices and are more resistant to enzymatic hydrolysis [21]. The structural arrangements of the A-type or B-type crystallites markedly influence their digestibility. Generally, a higher susceptibility to hydrolysis has been reported for the A-type crystallites than the B-type crystallites [63]. A-type and B-type starches differ in the packing of their double helices and in their water content [64]. The shorter double helices and interior crystallites of the A-type starches are more readily digestible and contain larger amounts of RDS and SDS than the B-type starches [65].

A comprehensive account of the enzymatic digestibility of native uncooked starches from different sources has been given by Dreher et al. [66–68]. The authors suggest that cereal starches are more digestible than tuber and legume starches, which may be attributable to the presence of numerous pinholes in the surface layers of the granules and pores, which penetrate toward the interior of the granules from cereal sources, such as corn. These pores in the granules facilitate the entry of amylases, allowing the digestion of the granules.

Huber et al. demonstrated that both the crystalline and amorphous regions in cereal starch granules have the same granule center, as shown in Fig. 2.5 [69]. Enzymatic digestion begins at the surface pores and interior channels, and then digestion gradually enlarges the channel by simultaneously digesting the crystalline

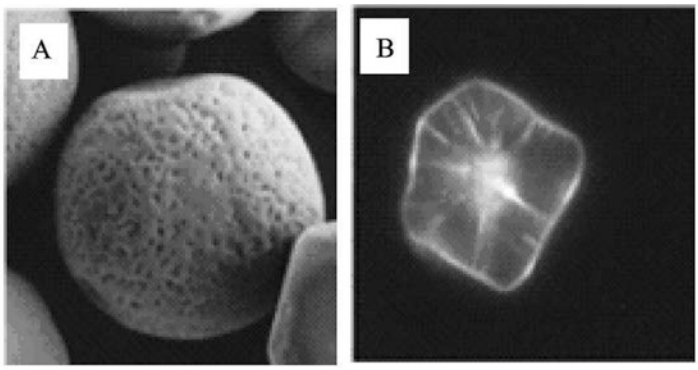

Fig. 2.5 (**a**) (SEM) Surface pores of a cereal starch granule; (**b**) (micrograph) the interior channels and cavity revealed with an aqueous solution of merbromin [69]

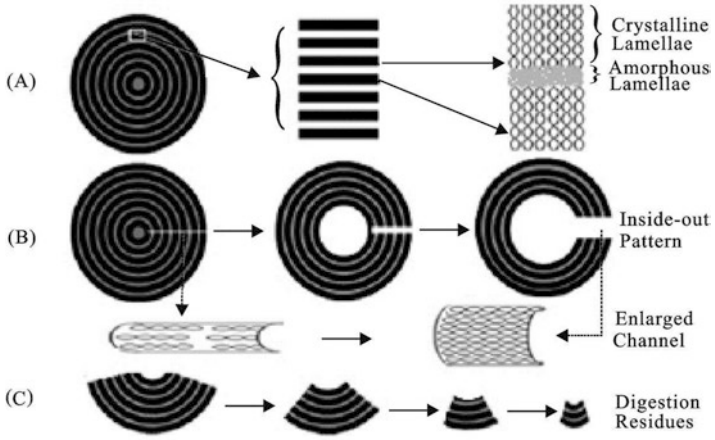

Fig. 2.6 Schematic representation of the dynamic side-by-side digestion mechanism and resulting static inside-out digestion pattern [70]

and amorphous regions. This explains this slow digestion process. Figure 2.6 [70] shows that the digestion of the starch granules starts at the interior channels.

In general, starch is consumed after it is processed. An excess of water and high temperatures during processing cause starch gelatinization and destroy its granular structure. However, the granular structure of starch is retained in several low-moisture food products, such as biscuits [71].

The hydrolysis of native starches can vary greatly, depending on the interplay of a range of factors, but it is usually determined by the botanical origin of the starch, which determines its morphology and crystalline organization [72]. This offers a way to influence starch digestibility with breeding research and the selection of suitable crop varieties.

The diffusion of α-amylase into the substrate is considered an important step in hydrolysis. The interactions of starch with fiber, protein, and other food components can prevent the effective diffusion and adsorption of α-amylase [62]. The hydrolysis of starch was previously considered to start from the surface of the granule. However, native cereal starches, such as corn and sorghum starches, contain peripheral pores and channels that allow the penetration of α-amylase, resulting in an inside-out hydrolysis mechanism [70]. In contrast, potato starch and other B-type starches are digested from the surface of the starch granule [73], explaining the higher digestibility of cereal starches compared with tuber starches, such as potato starch [74, 75]. Tuber starches are generally more resistant to enzymatic hydrolysis than cereal starches, because of their larger granules, their surface properties, and their supramolecular arrangement. The large amounts of resistant starch in tubers, particularly the potato, and in fruits such as the banana have been reported both in vitro and in vivo [1], whereas cereal starches, such as rice, wheat, and barley starches, are highly digestible [76]. Native normal cornstarch, waxy starches, millet starches, sorghum starches, and legume starch reportedly display intermediate digestibility because they contain medium-to-high amounts of SDS [74, 77–79]. Part of the lower digestibility of millet, sorghum, and legume starches can be attributed to their interactions with protein, which forms a protective network around the granule.

2.3.2 Fine Structure of SDS and Its Digestibility

When starch is processed for use in food, the starch is gelatinized. At this time, the molecular structure of the starch is the only factor determining its functionality and nutritive peculiarities. The molecular structure of starch includes the ratio of amylose and amylopectin and the fine structure of amylopectin [80].

At the molecular level, the crystallite structure and the packing of the amorphous phase influence the enzymatic susceptibility of starch [73]. The unit chain length of amylopectin correlates with its digestibility, and the proportion of the amylopectin unit chain length with DP 8–12 or DP 16–26 correlates positively and negatively, respectively, with its hydrolysis [81]. Longer chains form longer and more stable helices, which are further stabilized by hydrogen bonds distributed throughout the entire crystalline region, which further reduce its digestibility.

The nature of starch also influences its digestibility and the postprandial glucose response. Starches high in amylopectin have been shown to be digested more quickly than those high in amylose [82], probably because amylopectin has many more nonreducing chain ends than amylose, to which digestive enzymes can attach [83].

Some researchers have shown that the fine structure of amylopectin, with its high branching density and either long or short internal chains, causes its slow digestion. Therefore, the inherent molecular structure of amylopectin is responsible for its

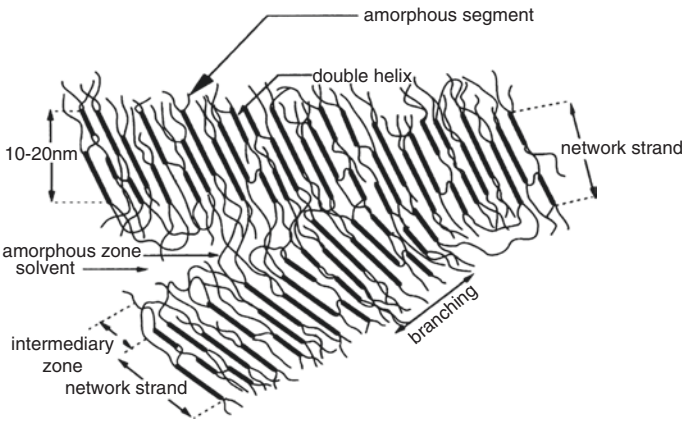

Fig. 2.7 Structure of amylose gel, a structural feature of recrystallized SDS [85]

slow digestion [63, 84]. The structure of SDS may include imperfect crystallites and amylopectin, with a high branching density, which probably cause its slow digestion [3].

An illustration of retrograded starch chains and the arrangement of the amorphous material that determine the formation of SDS is presented in Fig. 2.7. It is proposed that amylose chains aggregate in an infinite three-dimensional network, linking the microstructure and the macromolecular organization of starch. The chain segments inside the crystallites are disposed obliquely relative to the microfiber axis. Therefore, the network of strands consists of contiguous associated blocks aligned along the length axis of the microfiber. Double helices are then linked to other helices by loops of amorphous amylose segments, dangling in the gel pores. This fraction is responsible for the hydrodynamic behavior of amylose gels [85].

2.4 Physicochemical Properties of SDS

2.4.1 Postprandial Glycemic Response

The slow digestion property of SDS products can be confirmed with a postprandial glycemia test. The microencapsulation of normal cornstarch by zein protein was investigated, and the starch capsules displayed a significant increase in SDS [86]. In a further in vivo study using a mouse model, both the cornstarch material and the encapsulated starch material showed slow digestion profiles, with the prolonged and sustained elevation of blood glucose, confirming that microencapsulation did not alter the inherent slow digestion property of native normal cornstarch.

Dietary carbohydrates are the main source of energy in the human diet and are also the main determinant of postprandial blood glucose levels. In recent decades, the effects of carbohydrate-rich diets on human health have been debated because of

their potential untoward effects on glycemic control and plasma lipid concentrations. A high intake of refined carbohydrate foods has been particularly associated with increased plasma glucose and insulin levels in the postprandial period, the elevation of fasting and postprandial plasma triglycerides, and a reduction in high-density lipoprotein (HDL)–cholesterol levels [87–89]. A large body of evidence indicates that blood glucose concentrations are an important and independent risk factor for cardiovascular diseases, not only in diabetic patients but also in individuals with normal fasting glucose levels.

Delayed dietary carbohydrate digestion and absorption may have significant beneficial implications for the prevention and treatment of metabolic disorders. Many factors influence the digestion of carbohydrates in the small intestine, including their viscosity, the physical form of the food, the cooking and processing methods, the type of starch (amylose or amylopectin), the presence of antinutrients, and the amounts of fiber, fat, and protein present [89].

The postprandial glycemic and lipid responses are linked to the risk of chronic diseases. The rate of digestion of dietary carbohydrates in the intestine plays a clinically relevant role in the regulation of the postprandial metabolism. After a meal, glucose levels are modulated by the rate of carbohydrate digestion in the small intestine and by the fermentation of undigested carbohydrates in the colon. Moreover, when the carbohydrate reaches the colon, it has a beneficial effect on the composition of the colonic microbiota and on short-chain fatty acid production, which improves the metabolism of glucose and lipids. This explains why a diet based on legumes, vegetables, fruits, and high amounts of SDS can significantly improve an individual's cardiovascular risk profile, particularly in type 2 diabetic patients, and can substantially reduce the overall risk of cardiometabolic diseases [90].

2.4.2 Gelatinization Parameters

When heated in excess water, starch granules undergo gelatinization in three distinct stages: the granule swelling, the disruption of the ordered (crystalline and molecular) structures, and the solubilization of the starch molecules [91]. Gelatinization causes irreversible changes in the starch properties, including its water uptake, granule swelling, crystal melting, birefringence, solubility, and viscosity. These changes greatly affect the functional properties of starch and its digestion. These changes also involve a sequence of thermal events that results in the phase transition of the starch granules. When starches are heated in limited water, biphasic endotherms are often observed with differential scanning calorimetry (DSC), which is related to the gelatinization and melting of the starch crystallites [92].

In the SDS gelatinization studies mentioned above [13, 14, 28, 29], the thermal parameters of modified and native starches were determined with DSC, and the results showed that the gelatinization parameters of starch differ considerably before and after modification.

2.4.3 Starch Pasting Properties

Pasting involves the swelling of the starch granules, the leaching of carbohydrates, the formation of a three-dimensional network of leached molecules, and the interactions between the granule remnants and the leached material. It is determined by the botanical origin of the starch, its amylose content, the distribution of amylopectin chain lengths, the swelling power, the starch concentration, and the processing conditions, such as the shearing and heating rates.

The determination of starch pasting profiles with a rapid visco analyzer (RVA) was originally proposed by Charles (Chuck) Walker in rain-damaged wheat [93]. RVA starch pasting profiles are currently used extensively in the human food industry, e.g., to determine the different parameters related to the starch pasting properties of cereals and starchy foods [86].

The typical profile of a starch sample analyzed with RVA indicates the main parameters measured during the analysis. The pasting temperature provides information about the minimum temperature required to cook a given sample [94]. Other parameters, such as the rate of breakdown in viscosity and the hot paste viscosity or trough, depend upon the temperature and degree of mixing [94]. The reassociation of the starch molecules during cooling is commonly referred to as the "setback." It involves the retrogradation of the starch molecules and has been correlated with the texture of various products. The final viscosity of the starch is the parameter most commonly used to define the pasting properties of a given sample.

In recent years, several authors have evaluated the use of multivariate data analysis techniques to better interpret RVA profiles and have obtained further information about the starch pasting properties of a sample [95, 96].

The RVA results of Xu and Zhang [86] showed that encapsulated starch was considerably altered. In that study, the microencapsulation of normal cornstarch with zein protein and its slow digestion property were investigated. A significant increase in SDS was detected in the starch capsules (weight ratio of zein to starch, 1:6) containing plasticizers (glycerol and oleic acid) after high-temperature (70 °C) treatment. The temperature at peak viscosity increased, and the peak viscosity of the microencapsulated starch was substantially reduced, indicating improved thermal resistance after microencapsulation. These data suggest that the starch granules were densely packed in the zein matrix after the high-temperature treatment, which may slow the enzymatic digestion and generate a relatively high amount of SDS.

2.5 Functions of Slowly Digestible Starch

Studies of the benefits of SDS are limited. The potential health benefits of SDS are linked to stable glucose metabolism, diabetes management, mental performance, and satiety.

2.5.1 SDS and the Metabolic Response

The metabolic effects of carbohydrates, particularly glucose, are related to the rate of carbohydrate absorption after a meal. A common measurement that assesses these effects is the GI. Positive associations have been established between the dietary GI and the risk of colon and breast cancer [97]. SDS has a medium-to-low GI and therefore reduces the glycemic load of a food product compared with that of RDS, which has a high GI [10].

The limited research available in humans suggests that SDS blunts the postprandial increase and subsequent decline in the plasma glucose and insulin concentrations, leading to prolonged energy availability and satiety, compared with more rapidly digestible starch.

There have been few reports of the effects of SDS on glucose tolerance or energy expenditure. The ingestion of 35 g of available carbohydrate as cornstarch or waxy cornstarch (both SDS) resulted in a smaller and more sustained increase in plasma glucose than did maltodextrin (an RDS) [98]. In healthy young women, a meal containing slowly digestible waxy cornstarch resulted in lower peak concentrations of plasma glucose and insulin than a meal containing cooked, rapidly digestible cornstarch [99]. In young men, the consumption of uncooked cornstarch (an SDS) blunted their plasma glucose and insulin responses. During the first 120 min after consumption, the area under the glycemic dose–response curve for the SDS was smaller than that after the consumption of glucose, whereas after 120 min, there was no difference between the two areas [100].

Sands et al. examined the effects of uncooked waxy cornstarch (an SDS) on postprandial plasma insulin and glucose and on the whole-body energy expenditure and appetites of men and women. The consumption of uncooked waxy cornstarch led to lower postprandial glucose and insulin concentrations but had no effect on postprandial energy expenditure or appetite compared with the consumption of cooked, rapidly digested waxy cornstarch [101]. These findings are similar to those of Wachters, who reported that the consumption of 50 g of available carbohydrate from an SDS, uncooked cornstarch, led to smaller glucose and insulin areas than the consumption of 50 g of glucose [99]. In conclusion, these results establish that the consumption of native waxy cornstarch blunts the postprandial glucose and insulin responses in humans, potentially providing a steadier supply and release of energy over a specific period than the RDS maltodextrin.

The digestion of alginate-entrapped starch microspheres as a source of SDS generates short-chain fatty acids in the alimentary canal, including propionic, acetic, and n-butyric acids, which help to prevent colon cancer but produce little energy [102].

The intake of slowly available glucose improved the metabolic profiles of obese insulin-resistant subjects [103], particularly reducing postprandial insulinemia and lowering the levels of circulating triacylglycerols and the apolipoproteins in triacylglycerol-rich lipoproteins. RDS and SDS also differ in their ability to stimulate the secretion of the gut incretin hormones.

2.5.2 SDS and Diabetes

Postprandial hyperglycemia leads to insulin resistance and ultimate pancreatic β-cell failure. This results in noninsulin-dependent diabetes mellitus, which accounts for 90% of all diabetes cases.

The occurrence of obesity-related problems is currently increasing in response to modern lifestyles, the consumption of excessive dietary fat, and a reduction in physical activity. Obesity-related problems also lead to complications such as hyperlipidemia, nonalcoholic fatty liver disease, various cardiovascular diseases, and diabetes in humans. In general, diabetes is a form of metabolic disorder that occurs with the dietary intake of excessive carbohydrates and lipids [104].

Type 2 diabetes mellitus (T2DM) is a common endocrine and metabolic disease caused by an absolute or relative lack of insulin in the blood, resulting in metabolic abnormalities such as obesity, hypertension, low levels of HDL, elevated triglyceride levels, hyperglycemia, and resistance to insulin [105]. The complications of T2DM are associated with obesity, oxidative damage, dysfunction of metabolism, and eventual organ failure [106, 107].

Apart from genetic causes, the dietary pattern of an individual plays a key role in the occurrence of metabolic syndrome, which is often attributed to the increasing influence of the western diet, which contains an excessive fat content and is poor in minerals and fiber [108].

With the increased occurrence of diabetes in humans, current research has focused on the development of drugs to treat and control T2DM. Various drugs have been developed, but the long-term use of antidiabetic drugs can have considerable adverse effects, with symptoms of hypoglycemia and kidney or liver malfunction [107, 109]. Because no medication is yet effective in the treatment of T2DM, current research is concentrated on the prevention or delayed onset of diabetes by exploring the functional adjuncts responsible for it.

This increase in metabolic syndrome has challenged food scientists to develop innovative food products that combine dietary satisfaction with disease management. Therefore, reducing meal-associated hyperglycemia is one goal in the prevention of diabetes mellitus. SDS has a beneficial metabolic effect on diabetes and is recommended for its prevention and management [10, 110]. Several processes are used to produce either components that remain undigested in the upper intestinal tract or an intermediate starch, which is digested slowly in the small intestine. In this way, the release of glucose is slowed, which is advantageous for diabetic patients.

SDS-containing breakfast foods also improve carbohydrate metabolism and reduce the insulin requirements of insulin-treated T2DM patients [111]. Because there is a lack of suitable sources, uncooked cornstarch is recommended as a source of SDS for those suffering diabetes. This can improve the glycemic response at the next meal and prevent evening hypoglycemia in diabetic patients who are treated with insulin [77].

2.5.3 SDS and Mental Performance

The consumption of foods containing high levels of sugar correlates with risk factors for cardiovascular disease, including impaired glucose metabolism, obesity, dyslipidemia, T2DM, and hypertension [112]. Many biological pathways are involved in these adverse outcomes, including the glucose-related dysregulation of vascular biology and vascular functions. Most studies of sugar intake and cardiovascular risk have been cross-sectional and based on patients' self-reported usual dietary habits [113].

A previous investigation of the effects of acute glucose ingestion on the resting cardiovascular function demonstrated its potent hemodynamic effects, which are characterized by increased cardiac output, heart rate, systolic blood pressure, and superior mesenteric artery flow and reductions in diastolic blood pressure and total peripheral resistance [114]. These glucose-induced hemodynamic changes reflect, at least in part, the increased demand of the gut for blood to maintain its digestive activities [115].

Evidence suggests that the acute ingestion of glucose increases the mental challenge-induced activity of the hypothalamic–pituitary–adrenal axis [116, 117] and the total peripheral resistance and that prolonged challenge increases the cardiac output [114]. The ingestion of a gelatin-based drink containing "complex carbohydrates" is associated with increases in cardiac output and systolic blood pressure, reduced total peripheral resistance at baseline, and an increased heart rate in response to mental challenge [118]. These studies are clinically important because elevated autonomic nervous system and cardiovascular responses to mental challenge and delayed recovery have been identified as risk factors for cardiovascular disease [119].

Previous studies have made mental efforts using indices of psychophysiology, particularly cardiovascular measures. Metabolic measures represent a complementary approach by which the investment in mental effort is explicitly linked to the process of energy mobilization [120]. Glucose provides energy for our brains. One study showed that glucose levels in the blood can influence mental performance, especially higher mental activities [121], and studies using glucose drinks have also demonstrated the positive effect of glucose, which tended to improve attentional performance by 8% ($P < 0.07$) [122]. When the specific effects of macronutrients on performance are evaluated, the effects of meals are less consistent. A limited amount of data is available on the effects of the carbohydrate absorption rate on cognitive performance.

Glucose regulation has been associated with cognitive performance in elderly subjects with normal glucose tolerance, and dietary carbohydrates enhance cognition in subjects with poor memories [123]. A literature review that focused on the physiological effects of starches concluded that glucose may influence both memory and mood [124].

2.5.4 SDS and Satiety

Most mammals, including humans, prefer foods and liquids rich in sugar [125, 126]. A preference for this macronutrient stems from both its sensory and postingestive properties and is regulated at the brain level [126]. Several central mechanisms underlie the drive to consume sucrose. For example, multiple studies assessing operant behavior have shown increased motivation to obtain sweet foods. Furthermore, sucrose intake, especially chronic intake, activates components of the central reward circuitry, for example, by modifying the expression of genes encoding opioid peptides and their receptors or by affecting the release of neuropeptides and neurotransmitters, such as dopamine and opioids [112].

Satiety is a complex phenomenon controlled by social, physiological, and psychological factors. The ability to balance energy intake and expenditure is critical to survival, and sophisticated physiological mechanisms have evolved to do this, including appetite control. Satiation and satiety are part of the body's appetite control system and are involved in limiting energy intake. Satiation is the process that causes one to stop eating, whereas satiety is the feeling of fullness that persists after eating, suppressing further consumption, and both are important in determining the total energy intake [113]. Satiation and satiety are controlled by a cascade of factors that is initiated when a food or drink is consumed and continues as the ingesta enters the gastrointestinal tract and is digested and absorbed. Signals of the ingestion of food energy are transmitted to specific areas of the brain that are involved in the regulation of energy intake, in response to the sensory and cognitive perceptions of the food or drink consumed and the distension of the stomach. These signals are integrated by the brain, and satiation is induced. When nutrients reach the intestine and are absorbed, a number of hormonal signals are released that are also integrated in the brain to induce satiety. In addition to these episodic signals, satiety is also induced by fluctuations in hormones, such as leptin and insulin, which indicate the level of fat stored in the body [113, 127].

The concept that blood glucose levels, determined by the carbohydrate intake, are the central regulator of satiety is based on the glucostatic theory of food intake regulation [128]. This theory maintains that low blood glucose can cause high blood insulin levels, which signal satiety. Campfield and Smith [129] reviewed our current knowledge of the complex regulatory mechanisms mediating the dynamics of blood glucose and meal initiation, which supported the proposition that transient declines in blood glucose promote hunger. A stable and low insulin response after a meal also seems to be important for the regulation of satiety, which supports the hypothesis that SDS has a beneficial effect on satiety. A study that compared slowly digested barley kernels with a white bread control reported similar results [130]. In terms of appetite, the ingestion of slowly digested barley kernels is reported to cause greater satiety over a 3-h period than white bread.

It can be concluded that SDS affects satiety-influencing factors, such as postprandial blood glucose and insulin levels. However, further study of the mechanisms of satiety is required, including gut hormones and meal composition.

2.6 Applications of SDS

As a new functional component or ingredient in novel product development, SDS can be widely used in solid or liquid processed food products, nutritional supplements, and drug preparations (tablets, emulsions, and suspensions). The amount of SDS added is selected to confer the desired functional properties, digestibility, and glucose release rate or some desirable balance of these parameters.

2.6.1 Applications in Foods

A wide range of techniques is used by the food industry to process various food materials. Processing changes the food structure and also influences the nutritional characteristics of the food, including its starch digestibility. SDS can be added to many food products in the form of a powdered ingredient to help control energy release, including in cakes, bread, cookies, pastries, pasta, pizza, cereals, chips, fries, candy, muesli, dressings, fillings, icing, sauces, syrups, soups, gravies, puddings, custards, cheese, yogurts, creams, beverages, dietary supplements, and diabetic products [131–133].

Oral glucose can be taken before prolonged vigorous exercise to increase endurance and to avoid the exhaustion associated with endurance sporting activities. SDS products, which can extend glucose release, may therefore provide athletes with necessary energy [134].

High-fat foods contain more calories than low-fat foods, and in light of the epidemiological link between fat intake and health, they increase health risks. The caloric content of fat is higher than that of carbohydrates, and the replacement of fats in typical foods with carbohydrates should reduce the calorie-associated health hazards [135]. Several essential requirements must be considered when carbohydrates are used as fat replacements in food, such as their unique flavors, mouthfeel, viscosity, and other functional and organoleptic properties.

Most SDSs that contain linear short chains are fat-like carbohydrates and may effectively replace one or more fats in foods. These starches are either partially or totally undigested and therefore contribute zero calories to food. Some SDSs provide a variety of fat-like textures in aqueous dispersions, ranging from oily to creamy to waxy. These fat replacements offer significant advantages in food applications, including the high-strength gels or thermo-reversible gels provided by SDS dispersions.

Microencapsulation is often used to preserve food components that are volatile or sensitive to oxidation, light, or temperature. Park et al. used this method to preserve some heat-sensitive SDSs and RSs. They encapsulated native and amylosucrase-treated waxy cornstarches with three different concentrations of sodium alginate: 0.5%, 0.7%, or 1.0%. The SDS and RS fractions constituted 57.5% and 97.7% of the encapsulated starch, respectively. After cooking, the proportions

of these fractions still ranged from 55.7% to 96.1%, depending on the type of starch and the concentration of sodium alginate added, whereas the unencapsulated starch contained between 2.9% and 48.3% SDS and RS after cooking. Therefore, replacing amylosucrase-treated waxy cornstarch with an encapsulated form allowed the development of new products with high SDS levels and different functional properties [136].

2.6.1.1 Functional Foods

A new slow-digesting rice starch (Ricemic) has been developed at the US Department of Agriculture (USDA) Southern Regional Research Center and is used to maintain stable blood sugar levels in diabetics and to provide athletes with a steady energy supply to maintain their endurance [11].

Starch-based cereal foods and whole kernel foods have been developed with low GIs and high SDS loads. For example, EDP® ("energy delivered progressively") can be found in both European and Chinese markets [11].

2.6.1.2 Slow-Release Energy Beverages

The satiating power of foods is related to their energy and volume [137] and might also be related to their fiber content. The Institute of Medicine (Kathmandu, Nepal) defined dietary fiber as those indigestible or weakly digestible carbohydrates that occur naturally in plants, so SDS can be considered a kind of dietary fiber [138]. The addition of fiber to foods and beverages can provide volume and reduce the energy density of the food and can increase the viscosity of liquid or semiliquid foods. Both dietary and functional fibers have been shown to promote physiological processes that are associated with satiety. For example, fiber can slow gastric emptying, reduce the GI of foods, modify the release of gastrointestinal hormones, and alter the absorption of other nutrients [139, 140].

Jolly-Zarrouk et al. investigated extended energy beverages containing a high level of SDS (1.5%) prepared with a hydrothermal treatment (35% moisture, 100 °C for 60 min), such as Milo®, Nesquik®, and Migros® [141].

2.6.2 Applications in Medicine

Starch, a natural carbohydrate polymer, is cheap, abundant, and renewable, and its biodegradability, biocompatibility, and bioabsorbability make it suitable for pharmaceutical applications [142]. Starch can be thoroughly absorbed by the human body without any allergic or toxic effects [143]. The interactions between the functional groups in the starch matrix and those in other compounds strengthen the capacity of starch to bind and entrap wide ranges of hydrophilic and hydrophobic

compounds. In contrast to lipid- or protein-based carriers, starch-based delivery systems provide a better protective shell for bioactive compounds at high processing temperatures because they are thermally stable [144]. These advantages of starch materials, together with the diversity of starch modifications, make starch and its derivatives ideal candidates for use in drug delivery, tissue engineering, and wound dressing.

Recent studies have focused on the modification of starch for its use in drug delivery systems. For instance, starch nanoparticles synthesized from cornstarch (modified and unmodified) have been used to formulate two different types of nanoparticles used in drug delivery systems [145].

Given the characteristics of the enzymatic digestion that occurs in the upper gastrointestinal tract, SDS can be used in medicines as a novel, starch-based biodegradable carrier, which may prove useful in oral drug delivery systems that specifically target the small intestine [133]. For example, SDS can be used as a biomacromolecular film to coat pharmaceuticals to ensure that the medicines are released in the small intestine. SDS can also be used for the treatment of certain medical modalities. Wolf and Bauer reported its utility in treating glycogen storage disease and diabetes mellitus [146].

2.6.3 Application to Fodder

Starch is the main source of energy in poultry diets, comprising approximately 40% of the diet and contributing more than half of the metabolizable energy intake [147]. Therefore, variations in starch digestibility strongly affect the energy value of poultry diets. Despite this, starch digestion in poultry has received little attention until recently because it is seldom a problem in poultry fed a corn-based diet. Several studies have indicated that the starch in corn is almost completely digested by broiler chickens. The secretion of pancreatic amylase by chickens also increases as their ingestion of starch increases [148]. However, accumulating evidence suggests that starch is not fully digested by poultry and that its digestibility varies considerably among cereal species and cultivars within those species. Therefore, the factors that reduce starch digestibility in the total gastrointestinal tract or the ileum in poultry are critically relevant to the development of practical feed formulations [149].

Perhaps the most important factor affecting starch digestibility in poultry, at the total gastrointestinal tract or ileal level, is the accessibility to the starch fraction by digestive enzymes. This accessibility is determined by several factors, including granule size, shape, and surface area and the amylose-to-amylopectin ratio [21]. Briefly, the lower susceptibility of large granule starches to enzymatic hydrolysis has been attributed to their smaller granule-specific surface area, which may reduce the extent of enzyme binding and ultimately result in less hydrolysis than small granules [59].

Its excellent properties make SDS a suitable feedstuff or fodder material. Based on a patent of Winowiski [150], feed for ruminants that is rich in SDS may reduce

the rate of digestion by rumen microbes, thereby reducing the effect that the rapid consumption of fermentable grains can have on the rumen pH and the digestion of fiber. This may provide a more even flow of fermentable starch to support the microbial metabolism and may increase the proportion of starch from cereal grain consumption that ultimately arrives in the small intestine.

The consumption of SDS improves protein and energy utilization in broiler chickens, including superior feed conversion at the amino acid level [3]. The results of Weurding et al. suggest that the starch digestion rate is an important feed characteristic in broiler chickens. Broiler chickens grew faster and more efficiently on a diet containing SDS than on a diet containing RDS [151].

2.7 Conclusions and Future Directions

Because of its many functions, SDS has shown great potential utility as a fat replacement, in slow-release energy beverages, as a medicinal carrier, and in the preparation of fodder. The linear short chains released from amylopectin endow SDS with the mobility required for molecular alignment and aggregation, leading to the formation of gel networks and crystalline structures. SDS is hydrophilic and can hold water to form a gel network, and its use in controlled-release medicines is based on this property. A gel layer can immediately form on the surface of SDS-based tablets, which retards drug release. The retrogradation and recrystallization of these starches also contribute to the formation of SDS products. SDS can be used to prepare low-calorie foods and improve the fermentation processes of the gut flora in the colon.

SDS is an important kind of modified starch, with potential utility in a wide range of applications. Future research should focus on the various aspects of recent advances. These include the stabilization and protection of flavors, lipids, bioactive agents, and drugs from oxidation and enzyme hydrolysis. The accurate regulation of SDS fabrication with specifically designed components is another essential research focus. The functionality of vague SDS mixtures is highly variable, according to the preparation conditions. A most important aspect of future research is the rigorous evaluation of the health effects of consuming any SDS product. More industrial-scale applications of SDS in both the food and nonfood sectors should be thoroughly investigated. SDS should have extensive applications in foods, beverages, pharmaceuticals, cosmetics, fodder, and so on.

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