Chapter

Resistant Starch from Exotic Fruit and Its Functional Properties: A Review of Recent Research

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Abstract

Resistant starch is a functional food ingredient that can resist enzymatic digestion in the small intestine and fermentation in large intestine. Resistant starch has many benefits to human health by promoting a balanced blood sugar and beneficial gut bacteria. This review highlighted the sources of different exotic fruit starch, such as banana, jackfruit, *cempedak*, *durian*, and breadfruit. The functional properties of these exotic fruit resistant starches were covered in this review. The effect of resistant starch on glycaemic index of food was revealed. This review also discussed on the applications of resistant starch in the production of food products and their effects on food quality. The provided information through the overall review could especially benefit the food industry in producing functional food products with great consumer acceptability.

Keywords: resistant starch, banana, jackfruit, *cempedak*, *durian*, breadfruit, functional properties, glycaemic index, product quality

1. Introduction

Starch is the main glycaemic carbohydrate reserve in plants, including cereals, tubers, roots, and unripe fruits. Starch is considered the second largest natural biopolymer next to cellulose [1]. Dietary starches are important sources of energy for the majority of the world's population. Starch is a polymer with molecular formula (C6H10O5)n and contains two D-glucopyranose polymers, namely, amylose and amylopectin. Amylose is a glucopyranosyl linear polymer, whereas amylopectin is a glucopyranosyl chain polymer [2]. It contributes up to 70–80% of total carbohydrates in human diet. Starch plays a major part in human nutrition by supplying metabolic energy that enables the body to perform its different functions [3]. Nowadays, dietary guidelines are focused on lowering fat intake by increasing complex carbohydrate intake (i.e. starch and dietary fibre) [4].

Nutritionally, starch can be grouped based on its rate and extent of digestion: rapidly digestible starch (RDS), slowly digestible starch (SDS), and resistant starch (RS) [5]. Recently, the consumption of RS in daily diet has gained increasing worldwide attention due to its health-promoting benefits and functional properties. The starch molecules undergo several physical modifications, depending upon the type of starch and severity of the conditions applied during processing of starchy foods, leading to RS formation [6].

RS positively influences the functions of the digestive tract, microbial flora, blood cholesterol level, and glycaemic index (GI) and assists in the control of diabetes [3]. Apart from the potential health benefits of RS, another positive advantage is its lower impact on food sensory properties than traditional fibre sources. Starch contributes to the physicochemical properties of food products which are made from cereals, tubers, roots, legumes, and fruits. Among its desirable physicochemical properties are its swelling capacity, viscosity, gel formation, and water-binding capacity, which make starch useful in a variety of food [7].

Starch digestion rate is affected by the nature of food composition (e.g. phosphorylated starch, RS, dietary fibre, phytonutrients, protein, and fat content) [8]. In addition, the types of chemical structure and physicochemical properties of starch and fibre present in food are important to determine their effects in the gastrointestinal tract [9]. The types of carbohydrate as well as total amount of carbohydrates in food will affect the blood glucose level [10]. According to Foster-Powell et al. [11], different digestibility rates of carbohydrate is related with some physiological functions, which have different health effects, for example, reduction in insulinemic and glycaemic responses to food, hypocholesterolemic action, and protective effects against colorectal cancer.

The functional properties of starch must be considered when developing food formulations due to its influence on the quality of end products. Starch functional properties depend on the molecular structure composition of amylose and amylopectin together with the arrangement of their starch granules. Starch paste consistency depends on the gelatinisation degree and swelling power of starch granule. The paste texture is determined by viscoelastic deformation and depends on the strength of molecular bonds and amount of broken granules. In addition the paste or gel clarity varies from clear to opaque, and this property is related to light dispersion that results from the association between amylose and other components present in starch [12]. Therefore, the functional properties of the raw materials are influenced by variety, climate, and soil conditions where the plant is grown [13].

2. Resistant starch (RS)

Resistant starch is defined as a portion of starch that cannot be digested by amylases in the small intestine [14]. However, RS can be degraded through glycolysis by microorganisms in the colon even though at the first stage it cannot be digested or absorbed by amylase in the human digestive tract [15, 16]. RS was introduced in recent years as a functional food ingredient important to human nutrition. RS has become an attractive functional food ingredient in food processing among food manufacturers to develop new nutritional food products [16]. The RS degree of formation in food depends on the type of starch contained and adopted processing conditions, such as water content, pH, heating temperature and time, number of heating and cooling cycles, freezing, and drying. It is also influenced by the duration and storage conditions [17–19]. Moreover, Eroglu and Buyuktuncer [19] reported that cooking methods like steaming, baking, and autoclave cooking increased the amount of RS in food, whereas pressure cooking was found to decrease the amount of RS in food. Cooking methods, such as boiling, microwave heating, extrusion, and frying, have the potential to increase the amount of RS, depending on the source of starch and processing conditions.

RS content is an important parameter to be considered mainly from the nutritional point of view as starch in this form is less easily digested and may impart health benefits [20]. In addition, RS was revealed to have various health benefits, including the prevention of colon cancer, inhibition of fat accumulation, reduction of gall stone formation, increase in absorption of minerals, hypoglycaemic and hypocholesterolemic effects, and acceleration of probiotic growth [21]. A diet high in RS can reduce blood cholesterol and triglyceride levels due to higher excretion rates of cholesterol and bile acids [22].

RS has a unique equivalent behaviour to fibre which can escape from enzymatic digestion in the small intestine but be fermented in the large intestine by colonic microflora to serve as source of nutrient for the colonic bacteria [5, 23]. When the carbohydrate metabolises, it lowers the colonic pH and releases short fatty acids, such as propionate, butyrate, and acetate, to encourage the spread of beneficial bacteria in the intestine [18, 21, 24]. RS plays a vital role in health food manufacturing [5]. With its unique characteristic that is resistant to human digestive enzymes, RS is slowly broken down throughout the entire small intestine and then produces a slow release of glucose, and thus acts as an evidence for the low GI of indigested starch [25]. This can help to reduce postprandial response and promote glucose regulation in diabetes and control body weight for the obese, reducing glycaemic and insulinemic responses to food [26, 27].

There are five general subtypes of RS fraction in food: type 1 RS (RS I), type 2 RS (RS II), type 3 RS (RS III), type 4 RS (RS IV), and type 5 RS (RS V) [28]. The RS fractions are classified based on the nature of starch in food [5]. For RS I, it is corresponded to the physically inaccessible starches which are entrapped in the cellular matrix found in whole grains and seeds. RS II is native uncooked granules of some starches, such as starch in green bananas, raw potatoes, some legumes, and high amylose starches (i.e. high amylose corns), in which crystallinity makes them scarcely susceptible to hydrolysis. Meanwhile, RS III is retrograded amylose and amylopectin during food processing which causes a reduction in glycaemic response [29]. This starch is found in cooked and cooled food such as potatoes, bread, and corn flakes. Chemically modified starches generally belong to RS IV, and their molecular structures are chemically altered in many ways. RS IV is used by food manufacturers to improve the functional characteristics of starch [3]. RS V comprises amylose-lipid complexes, which have helical structures with fatty acid tails at the central cavities of the inclusion complex formed by alpha-amylase and polar lipids [5, 30]. These types of starch require higher temperatures for gelatinisation and are more susceptible to retrogradation [18].

3. Functional properties of resistant starch produced from exotic fruits

3.1 Banana

Several studies have reported that banana starch contains a high level of amylase that is often related to a high retrogradation [24, 31, 32]. Vatanasuchart et al. [31] reported that flour produced from indigenous banana cultivars has a high content of apparent amylose. Several reports revealed that consumption of green bananas confers beneficial effects on human health. This is often associated with their high content levels of RS, dietary fibre (i.e. non-starch polysaccharides), functional components, and other nutritive values [24].

In addition, green banana, which is a rich source of complex carbohydrates, is mainly RS and fibres, which is an important functional food [33]. Green banana starch is highlighted as one of the good substitutes for the starch industry [32]. Moreover, bananas are also a good source of energy due to the presence of a large amount of starch and sugar. The slow digestion of unripe plantain starch is associated with its starch granule properties (i.e. amylase and amylopectin), and its physical characteristic is related to the plant cell wall that can contribute in lowering total starch gelatinisation [34].

Unripe bananas or green bananas were reported to contain high amount of RS II (i.e. ungelatinised starch granules that are protected from hydrolysis by the crystalline structure of the starch granule). The dense starch granules with crystalline structure property of green banana contribute to its high resistance to acid and digestive system enzyme (e.g. α-amylase) [35]. RS that is present in green banana helps to improve peptic ulcer and prevent damage of the mucosal lining [36].

A recent study showed that starch produced from the green banana variety of Mysore (Musa AAB-Mysore) had good physicochemical features and functional properties [37]. It is observed that starch from green variety of Mysore exhibited good swelling power which shows potential for its use in products that require water retention, such as meat and jellies. In addition, the low percentage of water loss during storage and low setback obtained by a folder profile study showed that starch is less prone to syneresis, which is one of the important factors to be considered during development of food products which require to be kept under refrigeration [37]. Fontes et al. [37] described the shape of starch granules of banana from the green variety of Mysore as ellipsoidal in shape with irregular diameters that range between axes of 10 μm and 100 μm and smooth surface. Another study done by Khawas and Deka [38] indicated that isolated culinary banana starch experienced restricted swelling and solubility profile and was unstable during freezing and thawing cycles. However, the starch demonstrated a high pasting temperature which indicated that culinary banana starches have high gelatinisation temperature and resistance towards swelling. Culinary banana starch exhibited a mixture of A-type and B-type polymorphs when observed under X-ray diffractometer. In addition, culinary banana starch has various functional groups which suggest C-type starch with a mixture of spherical and elliptical granules [38].

The banana starch was double-chemical modified by using two different cross-linking agents (i.e. phosphorus oxychloride and a mixture of sodium trimetaphosphate/sodium tripolyphosphate) [39]. The modified banana starch has a bigger average particle size than unmodified starch due to the swelling of the granules during chemical modification, and aggregates were also formed. The chemical-modified banana starches presented an A-type X-ray diffraction pattern with slightly decreased crystallinity as compared to the unmodified banana starch. In addition, the modified starch decreased the temperature and enthalpy of gelatinisation and the decomposition temperature which were due to partial disorganisation during chemical treatment [39].

Many studies were conducted to produce and characterise the RS from banana starch; for example, González-Soto et al. [23] reported that banana starch is a good source for RS production by autoclaving after starch debranching. According to González-Soto et al. [23], banana starch without treatment has higher available starch (80.5%) and lower RS content (9.1%) than the banana starch that was debranched for 5 h and longer (70.0–77.5% for available starch and 14.5–18.5% for RS). A recent study done by Khawas and Deka [38] indicated that the RS III produced from culinary banana starch through enzyme debranching and hydrothermal process showed remarkable changes in physicochemical, functional, morphological, and thermal characteristics when different processing conditions were employed. It was reported that the modification of starch to RS III occurred due to retrogradation of the amylose fraction. Accordingly, the temperature and storage conditions enhanced its formation. Through analyses of scanning electron microscopy, Fourier transform infrared spectra, and thermogravimetric analysis, the results revealed various significant morphological changes and was observed with increase in starch concentration and elicited prominent modifications in enzyme-debranched RS [38].

Furthermore, starch from the peel of *Agung* banana, variety of Semeru, was isolated and characterised by Hadisoewignyo et al. [2]. The study reported that the characteristics of the resulting processed starch from *Agung* banana peel met the required specifications with regard to its form, taste, odour, and the presence of hyllus and lamellae. Hyllus is an initial point of starch formation, while lamellae are smooth lines surrounding the hyllus. However, the white colour index (~56°) of *Agung* banana peel starch did not meet the required specifications (i.e. 95°; white colour) due to an oxidation process that occurred during the starch preparation. In terms of the original shape of starch, starch isolated from the peel of *Agung* banana showed a small particle size [2] as compared to the elongated and cylindrical shape of green banana starch granules [40]. Moreover, the gel of *Agung* banana peel starch was reported to be twice more viscous than cassava starch gel, which made it very suitable as an ingredient in various food and nonfood industries including pharmaceutical industries, especially in making a tablet dosage form (i.e. tablet binder) [2].

Subrahmanyan et al. [41] reported that banana pseudostem contains 44.80% starch. The banana pseudostem was reported to contain high-quality starch [41, 42]. The study reported that starch granules of banana pseudostem are irregular in shape and are bigger in size than those of fruit starch. It also has similar intrinsic viscosity to that of potato starch. The amylose content of the banana pseudostem starch compare well with that of banana fruit and potato starch (21%) [42]. In addition, Ho et al. [43] reported that banana pseudostem was high in RS (12.81%). Since there is no updated scientific data related to the functional properties of the RS produced from banana pseudostem, there is an urgency to search for the functional properties of RS produced from banana pseudostem, so that it can be used to produce various value-added functional food products in the near future.

3.2 Jackfruit

Jackfruit (*Artocarpus heterophyllus*) seeds are considered as by-product of the canned and chips food industries. It has long been used as food among the indigenous people in many areas of the world. The seeds are usually consumed boiled, steamed, roasted, or are eaten as a snack [12]. Jackfruit seeds are recognised by many research studies as a raw material for a new source of starch [12]. The jackfruit seeds have been well documented to contain an average of above 60% dry basis of starch [44]. Native jackfruit seed can contain a reasonable amount of type II RS due to its relatively high amylose content 24–32% [45]. Jackfruit seed starch is widely used in many manufactured food products as it provides a gelling property that is suitable for various baked products [46]. According to Noor et al. [47], jackfruit seed flour contains amylose of 26.4–30.21% and starch content of 81.05–82.52%. In terms of proximate composition, the isolated starch from jackfruit seed was reported to contain 8.39–12.20% of moisture, 1.09–3.67% of protein, 1.18–1.40% of fat, and 0.03–0.59% of ash content. Moreover, the study reported that compared with alkali and enzyme methods, distilled water was the most effective solvent in the extraction of starch from jackfruit seed by presenting the highest yield, protein content, amylose, and total starch [47].

Jackfruit seed starch has been widely studied on its physicochemical, functional, and pharmaceutical properties [12, 48]. The results revealed that it had potential as functional ingredient for application in food and pharmaceutical products [44, 49]. Rengsutthi and Charoenrein [44] reported that starch from jackfruit seed had higher amylose content and its granules were much smaller than corn starch and potato starch granules. With regard to the pasting profile, jackfruit seed starch paste showed more resistance to thermal and mechanical shear during cooking. In addition, the jackfruit seed starch granules were round and bell-shaped, and some had irregular cuts on their surface [12] with A-type crystallinity pattern [12, 44]. Zhang et al. [48] reported that the starches isolated from different varieties of jackfruit seeds, namely, four exotic jackfruit cultivars (i.e. *Artocarpus heterophyllus Lam*. cv. *Malaixiya No. 2*, *Malaixiya No. 3*, *Malaixiya No. 4*, *Malaixiya No.8*) and one local cultivar *Xiangyinsuo 1 hao*, had differences in average weight-average molar mass (Mw) of amylose and amylopectin and a fine amylopectin structure. The findings showed that jackfruit seed starch with a larger Mw of amylose and proportions of DP 25–36, DP ≥ 37, and chain length had lower peak viscosity, breakdown, final viscosity, setback, and adhesiveness but with a higher pasting and gelatinisation temperature, gelatinisation temperature range, gelatinisation enthalpy, and relative crystallinity. In addition, the local cultivar had lower amylopectin Mw, smaller particle size, and good amylopectin structure.

Kittipongpatana and Kittipongpatana [45] applied heat-moisture treatment to increase the yield of type II resistant jackfruit seed starch. It was reported that the native jackfruit seed contained approximately 30% w/w of type II RS and this amount was successfully increased to 52.2% w/w through heat-moisture treatment under the conditions of 25% moisture content, heating at 80°C for 16 h. In addition, thermal profile of the jackfruit seed RS showed an increase in the gelatinisation temperature as the moisture content was increased in the samples. Amylose contents of jackfruit seed RS exhibited a correlation trend with RS content. Jackfruit seed treated with heat-moisture treatment with higher RS demonstrated less swelling, while the solubility remained unchanged [45]. In addition, Madruga et al. [12] observed that the swelling power and solubility of jackfruit seed starch increased with increase in temperature, showing opaque pastes.

Jiamjariyatam [49] studied the effect of blends between wheat flour and jackfruit seed starch on the physical and chemical properties of batter coating. The wheat flour and jackfruit seed starch exhibited the A-type crystal form. Increasing jackfruit seed starch in blends was found to significantly increase amylose content and relative crystallinity in the starch mixture. An amylose content of 40–41% jackfruit seed starch was found to be suitable as batter coating for deep-frying.

3.3 *Cempedak*

Cempedak (*Artocarpus integer (Thunb.) Merr.*) belongs to the Moraceae family, which is in the same family as jackfruit (*A. heterophyllus Lam*.) [50]. *Cempedak* seeds are the underutilised by-product from the fruit industry which have promising commercial value because they contain an appreciable amount of carbohydrate, protein, dietary fibre, minerals, and various vitamins, such as B1, B2, B3, and C [51]. Research was conducted to determine the composition of *cempedak* (ripe and unripe) between flesh and seed. Lim et al. [50] reported that unripe *cempedak* flesh and seeds had higher crude fibre than that of ripe *cempedak,* while both ripe and unripe *cempedak* flesh contained more crude fibre than the seed.

Starch extracted from *cempedak* seed was also studied by Tongdang [52] for its compositions and properties. The study reported that pure starch recovered from *cempedak* seed yielded 17.5%. The *cempedak* seed starch comprised approximately 22.64% of amylose and 16.12% of RS. Amylose content in fruit seed starch is related to its viscosity as amylose molecules may reassociate to form a gel network during the cooling time after starch gelatinisation [52]. Microscopic morphology of *cempedak* starch granules are semioval or bell-shaped but differ in size, mainly in the range of 1–10 μm. When *cempedak* starch granules are viewed under normal light, hilum in the centre of the granules is observed. On the other hand, Maltese cross indicates the semicrystalline structure of *cempedak* seed starch granules are shown under polarised light [52].

Important starch properties that affect the characteristic of starchy food were also investigated in a study by Tongdang [52]. *Cempedak* seed starches swelled up slowly at 55–75°C, but its swelling power was rapidly increased at 75°C and kept increasing until 95°C. The swelling power showed by *cempedak* seed starch well agrees with its pasting temperature of around 82°C. Meanwhile, solubility of *cempedak* seed starch was also rapidly increased after 75°C. According to Su et al. [53], several factors can influence the swelling power and solubility of starch, such as granular size, molecular structure of amylopectin, and amylose to amylopectin ratio and composition altered by contaminants. High gelatinisation temperature (76.76–82.19°C) of *cempedak* seed starch can be an indicator of a strong bonding of molecules in the granules.

The utilisation of *cempedak* seeds with its nutritional properties by processing it into flour has become a new source of fibre in bakery products. *Cempedak* seed flour provides a good source of total dietary fibre (TDF) and RS [51]. The presence of dietary fibre in food products to consumers is becoming important since it shows beneficial effects on the reduction of cholesterol level and colon cancer risk [51]. RS escapes digestion and absorption in the small intestine which has a similar effect to some dietary fibres by conferring a protective effect against colonic diseases [54]. According to Yamada et al. [55], RS helped lower the GI value of food products by increasing the indigestible carbohydrate ingested in small and large intestines.

A study by Aziz and Zabidi [51] showed that the processing of *cempedak* seed into flour resulted in a composition change. It was observed that *cempedak* seeds flour (CSF) has higher insoluble dietary fibre (IDF) content of approximately 23.93% with a reduced RS content of approximately 14.77% than the original IDF content of 12.44% and RS content of 29.72% found in *cempedak* seeds. According to Vasanthan et al. [56], heating followed by subsequent cooling and dehydration during processing may convert the starch in *cempedak* seed into indigestible form. In addition, the reduced RS content in CSF was caused by the microstructural damage of the seed during processing which affected the water absorption capability [57]. It was also observed that the soluble dietary fibre (SDF) in *cempedak* seed and CSF comprised 16.0 and 9.6% of the total amount of dietary fibre, respectively. Dietary fibre promotes beneficial physiological effects, including the prevention of diseases due to its potential in reducing the risks of cancer and coronary heart diseases [58].

Substitution of non-wheat flour (i.e. CSF) in conventional wheat bread to improve its functional properties was of great interest in recent studies. Zabidi and Aziz [59] reported that CSF substitution at 20 and 30% in bread formulation significantly increased the RS content in bread samples. The increased RS content reduced the hydrolysis index value which resulted in a lower GI. During bread making, starch gelatinisation upon heat treatment and followed by cooling process resulted in the formation of retrograded starch (RS3) [57]. Moreover, enzyme-resistant amylose-amylose linkages that occurred upon retrogradation of starch aided in RS formation [60].

3.4 *Durian*

Durian (*Durio zibethinus* Murr.) seed is a waste that is comprised of 20–25% of the whole fruit [61]. *Durian* seeds are mainly made up of starch and mucilage (gum). Properties of starch isolated from *durian* seeds to indicate its potential in food applications have become a great interest in recent studies. Based on previous studies, recovery of pure starch from *durian* seed showed a low yield of 1.8–4.2% [62] and 10.1% [52] as compared to other aromatic fruit seeds (i.e. 17.5% in *cempedak* and 18.2% in jackfruit). The low pure starch recovery was due to the presence of gum in *durian* seeds, which absorbed a large amount of water [63] that trapped starch granules in a viscous suspension [64]. *Durian* seed starch showed an average granular size of 4–5 μm which was closely associated to the swelling power and viscosity of starch [52].

According to Tongdang [52], amylose and RS contents of *durian* seed starch were about 23 and 5%, respectively. Amylose content is crucial to functional properties of starch since high amylose is linked to high RS level in processed starchy food [65]. Starches that contain a low amount of amylose degrade faster than starches with a high amount of amylose [66]. Malini et al. [67] also reported that *durian* seed flour (DSF) contained 22.35% amylose and 66.33% amylopectin, suggesting that DSF contained similar amylose content with other common starch (i.e. tapioca). Amylose in the flour is important in the gel formation with a firm characteristic, while high amylopectin content is associated with the sticky property [68]. Flour with higher amylopectin content gelatinised faster [69] and reached a higher peak viscosity [67]. Due to similar amylose and amylopectin contents, it was found that DSF can be partially utilised to substitute tapioca flour as a filler ingredient in meatball without affecting its organoleptic quality [67].

A recent study of Baraheng and Karrila [64] was conducted to produce and characterise the *durian* seed flour and *durian* seed starch. The study reported that whole *durian* seed flour (WDSF) had lower starch content than demucilaged durian seed flour (DDSF), while durian seed starch (DS) contained the highest starch content. WDSF contains both starch and non-starch polysaccharides (gums). The removal of mucilage, which was considered a dietary fibre [70] led to an increase in starch content with a reduction in fibre content. *Durian* seed starch showed a pasting temperature of 76°C with its swelling power rapidly increased from 55 to 75°C [52]. Due to the presence of mucilage that enhanced water absorption [71], WDSF exhibited higher swelling power, water absorption capacity, peak viscosity, as well as emulsifying capacity and activity than that of DDSF and starch. However, WDSF showed the lowest gel hardness but highest syneresis in which water was released from gel at lower storage temperature [64]. These functional properties of WDSF suggest that it has potential to be used in hydrated product, emulsifier, and fat replacer, but it is not applicable in typical frozen food [64].

Innovative utilisations of the *durian* seeds as raw materials in food preparation is much encouraged. A recent study by Kumoro and Hidayat [72] on functional and thermal properties of fermented *durian* seed flour by using *Lactobacillus plantarum* revealed the potential of fermented *durian* seed to be used in the substitution of wheat flour as raw material. Fermentation produces acid and alters starch composition and morphology, increasing the gelatinisation temperature of *durian* seed flour (i.e. from 63.37 to 66.24°C) which is closer to that of wheat flour (i.e. 70.30°C) [72]. Mestres et al. [73] also described that fermentation may induce changes on the conformation of amylose and amylopectin in starch granules, which led to the alteration of gelatinisation temperature. On the other hand, fermented *durian* seed flour has higher fibre content and lower fat content, showing its superiority and high potential applications in food industry over wheat flour [72].

3.5 Breadfruit

Breadfruit (*Artocarpus altilis*) is rich in carbohydrates of approximately 76.7% [74] and has potential to be commercially processed into flour and starch. Breadfruit starch size is small with a granular size of 3.0–7.9 μm and is irregular in shape (i.e. spherical, elliptical, and polyhedral) [75]. Breadfruit starch has amylose and amylopectin content of 22.52 and 77.48%, respectively, and has moderately high breadfruit starch yield of 14.26%. It has shown its commercial value in industrial food utilisation [76]. In addition, the high amylose content of breadfruit starch and its capacity to resist digestion suggest that products fortified with breadfruit can help to regulate blood sugar levels [76, 77].

Application of native breadfruit starch as food additive or functional ingredient is limited due to its poor paste clarity, readily retrograded characteristic [75]. Useful information gained from the study on breadfruit starch modification is necessary. In a study by Marta et al. [75], breadfruit starch was modified by using different thermal processes to characterise its physicochemical and pasting properties. Native breadfruit starches undergo changes in granule morphology, crystalline characteristic, pasting, and functionality due to heat-moisture treatment (HMT), microwave heating treatment (MHT), heat pressure treatment (HPT), and osmotic pressure treatment (OPT). Partial gelatinization, indicated by swelling, separation, and granular aggregation/fusion [78], caused HMT-treated and HPT-treated starches granules to lose their physical integrity. In addition, the X-ray diffraction pattern of the breadfruit starch changed from typical B type to A + B type due to HMT, MHT, and HPT, whereas OPT produced A-type breadfruit starch. Starch granules of A type and B type differed in their water content and packing of double helices [65] which were caused by the 36 water molecules vaporisation in the central channel of the B-unit cell and movement of a pair of double helices into the central channel [79]. Tan et al. [80] also described that transformation of crystalline structure of starch (i.e. from B type to A type) during HMT increased the SDS and RS contents in breadfruit starch. The higher compacity of A-type crystalline structure and the A-type amorphous lamellae which also had tight packing with higher density [81] could improve the enzyme resistance of starch during digestibility [80].

In respect to functional properties, thermal-modified breadfruit starch by using HMT, HPT, and OPT showed higher pasting temperature (i.e. $\geq$76.65°C) than native starch [75] due to the formation of a stronger crystalline structure (i.e. complex bonds between amylose in the crystalline region and amylopectin in amorphous region) which required water absorption of starch at higher temperature [82]. In addition, peak viscosity of thermal-modified breadfruit starch reduced significantly [75] which might be due to the increase in the extent of amylose-amylose and amylose-amylopectin chain interactions that occurred during the modification process [83].

Furthermore, breadfruit starch showed its potential use in fermented product indicated by previous studies. Haydersah et al. [84] observed that amylolytic lactic acid bacteria (ALAB) affected the digestibility of breadfruit starch by decreasing RDS content with an increase in RS content. Increased RS content in fermented breadfruit might be associated with the formation of limit dextrins that resulted from the action of α-amylase on amylopectin [84] as well as the formation of type 3 RS due to starch retrogradation during processing [8, 85]. With increased RS content after fermentation, breadfruit showed its value in the development of fermented products with prebiotic properties since RS can trigger increased production of short-chain fatty acids to stimulate the microbiota of the human gastrointestinal tract [86]. Fermentation also reduced apparent viscosity of gelatinised breadfruit flour and changed its consistency from a thick sticky gelatinised form into semiliquid/liquid product [84].

4. Effects of resistant starch fortification on glycaemic index of food

Nowadays, the public have great interest with regard to the possibility of controlling the blood glucose level by altering the glycaemic impact of carbohydrate intake. Glycaemic index is one of the preferred tools used for ranking food with regard to the rate of blood glucose absorption level after food ingestion [5, 87]. GI ranks carbohydrate-containing food based on their blood glucose level effect. The postprandial glycaemic responses of carbohydrate-rich food and meals potion vary widely. Therefore, food is categorised according to their postprandial glycaemic responses with guidance of GI values [87]. Food can be grouped into three GI categories, namely, low GI (≤55), medium GI (55–69), and high GI (≥70).

Food that is categorised as a low GI usually contains a low concentration of soluble sugars but with a high concentration of unavailable carbohydrates [88]. According to Truswell [89], a low GI characteristic of food is usually linked to the RS content. Food with high RS content has more resistance to carbohydrate digestion and hence lower glucose absorption to prevent extreme blood glucose fluctuations, thus lowering the glycaemic level [87, 90]. Moreover, food that contain slow-digesting carbohydrates have influence on prolonged satiating effects, as these types of food are more satisfying and satiety and thus increase the time elapsed between meals. Food with high amount of RS could be qualified as functional food and have high market opportunities. On the other hand, readily digestible carbohydrates could accelerate the elevated blood glucose level and insulin secretion, which directly lead to various health complications [91].

Plantain flour has market potential due to its favourable characteristic of being able to lower the GI of food then release glucose at a slower rate than high-GI food. This feature is to be useful in the innovation of healthy diets for diabetic and obese individuals. Agama-Acevedo et al. [92] found that low estimated glycaemic index (EGI) cookies can be produced by substituting unripe banana flour for wheat flour. Food produced by incorporating high level of RS is one of the ways to lower the GI of food [27, 92]. According to Saifullah et al. [93], noodles made of green banana flour has lower EGI value than control noodles (i.e. noodle made of 100% wheat flour). A research done by Okafor and Ugwu [94] showed that green banana and plantain have high and slow digestible starch with low GI value. This is due to the presence of high content of RS and dietary fibre of unripe plantain [94]. Another study performed by Choo and Aziz [95] showed that noodles prepared by partial incorporation of green banana flour for wheat flour had significantly reduced the EGI level of the noodles.

In addition, low GI rice noodles were developed by Srikaeo and Arranz-Martinez [96] by using fortified rice flour enriched with amylose and resistant starch. Another research conducted by Srikaeo and Sangkhiaw [97] found that GI value of the rice noodles could be lowered to 51.84 (low GI food) by replacing tapioca starch with high amylose maize starch at 60% level in processing of rice noodles.

Native breadfruit starches contain 2.99% of SDS and 8.42% of RS [80]. Since breadfruit contains an appreciable amount of RS that could lower the glycaemic and insulinemic responses, there is a growing interest towards the utilisation of breadfruit in a wide range of products. Noor et al. [98] reported that breadfruit flour had higher crude fibre of 4.85% than commercial wheat flour, which contained 0.23% crude fibre. According to Zakaria et al. [99], the 5% substitution of breadfruit RS in bread formulation gave a lower GI value of 76 than GI value of 97 showed by control bread. A study from Widanagamage et al. [100] also reported a significant lower GI value of 64 for breadfruit when white bread was used as a standard food for comparison. By using 100% of glucose as a standard food for comparison, boiled breadfruit showed a GI value of 47 [101]. Based on compiled studies, Turi et al. [102] suggested that cooked breadfruit has low to moderate GI which is a potential to be used in controlling diabetes.

5. Effects of resistant starch fortification on food quality

Fortification of RS to food can provide alternative ways to fill in the gap between the current RS intake and recommended intake amounts. In parallel, consumer demand for healthy food has grown significantly during the last few decades, whereby preference is given to food that contain RS due to its health benefits. This attention has created a good investment opportunity for food manufacturers to incorporate RS into a wide variety of food products, such as bakery products, dairy products, noodles, and pasta. However, manufacturers need to be wise about the RS types and amounts fortified to their products because adding RS to food creates alteration to the product formulation and can adversely affect the quality of many processed products, such as breads and other bakery products, pasta, and other extruded products.

RS can be used as a functional food ingredient for producing different food products to improve their nutritional value by increasing the fibre-like fraction. From the industrial point of view, RS has a low calorie profile and can be used as a bulking agent in reduced sugar or reduced fat food formulations. RS does not compete for the water needed by other ingredients as it significantly holds less water than traditional dietary fibre and allows easier processing because it does not contribute to stickiness. This may be advantageous in low moisture product productions, such as cookies and crackers. In most applications, it does not alter the taste, texture, or appearance of the food [3]. Moreover, according to Sajilata et al. [21], food products supplemented with RS has no negative effect on the texture or taste of the end product. These food products have received greater consumer acceptability and better palatability than food products supplemented with dietary fibres.

According to Nimsung et al. [103], a substantial percentage of RS present in bananas has capability to promote significant health benefits to food products. Several reported studies showed that an increase in RS content of food products (e.g. pasta, bread, and cookies) that was incorporated with unripe banana [35, 93, 104]. A research done by Juárez-García et al. [35] indicated that green banana flour contained high total starch (73.4%), in which RS represented 17.5%. Several studies demonstrated that the RS content of food products (i.e. noodles, spaghetti, pasta, and cookies) could be improved by the substitution of green banana and unripe plantain [92, 93, 95, 104].

According to Amaral et al. [18], it is technically possible to increase the RS amounts in food. The study investigated factors, such as formulation, loaf size, baking conditions, and storage conditions (i.e. time and temperature), that might affect the formation of RS in wheat bread. Findings indicated that RS content of wheat breads was enhanced by a higher level of moisture in the dough and a larger loaf size of the final product. An extended baking process also increased the RS formation. Storing bread at room temperature for 3 days demonstrated further enhancement of the RS content. Moreover, the RS content of wheat bread could be increased by manipulating the ratio of ingredients and processing time [18]. Studies performed by Sankhon et al. [6] showed that there was improvement in bread RS content as lower temperatures, and longer baking times were applied.

A recent research article [105] reported the substitution of RS for bread flour at 10% without detrimental effect on bread qualities. However it caused lighter crumb colour and lowered the specific volume when higher substitution levels (20 and 30%) of RS were in bread formulation for bread making. In addition, at 30% substitution level, the microstructure of crumbs showed less structural integrity and a coarser network structure [105]. The bread loaves containing RS presented harder bread crumb than the bread without RS substitution [105]. These obtained results were not in line with the reports from Korus et al. [106], whereby the study found that the crumb hardness was reduced with increase in the amount of RS in bread. Besides, the total dietary fibre of bread with RS was also found to increase to 89% as compared to bread without RS (control) [106].

Jiamjariyatam [49] studied on the effect of the blends between wheat flour and jackfruit seed starch on the physical and chemical properties of batter coating. It was found that the amount of oil absorption in the battered product significantly decreased with increase in jackfruit seed starch in the mixture. Higher jackfruit seed starch content in the batter provided greater homogeneity with a fine starch network and less porosity. In terms of sensory evaluation, adding jackfruit seeds starch in batter coating results in increased hardness and crispness, but decreased brittleness, puffiness, oiliness, and oil coating. The study concluded that the ratio of 50:50 (wheat flour:jackfruit seed starch) in batter coating system gave the highest score in overall preference [49].

Utilisation of jackfruit seed starch as a thickener and stabiliser in chilli sauce was successfully developed by Rengsutthi and Charoenrein [44]. Findings showed that the jackfruit seed starch was suitable as a thickener and stabiliser in chilli sauce because the chilli sauce with jackfruit seeds starch had the lowest serum separation and highest viscosity during storage at 37°C for 4 weeks [44]. Moreover, research by Rengsutthi and Charoenrein [44] showed that the jackfruit seed starch can be a useful stabiliser in a high acid sauce.

Pasta with lower glycaemic response was developed by adding different types of RS [107]. Findings indicated that the addition of resistant starches influenced the quality of both the raw and cooked pastas but had no effect on cooking quality (i.e. water absorption, cooking loss, swelling index, and dry matter) and sensory characteristics of pastas. On the other hand, a study on instant noodles showed that steaming followed by frying of noodle strands resulted in a slight increase in RS content at approximately 1.2 times. In addition, storage of instant noodles for 60 days at room temperature (~25°C) showed a significant increase in RS content by 1.4 times. Therefore, storage could help in RS formation [90].

6. Conclusion and perspectives

Resistant starch is one of the functional ingredients that is receiving attention due to its unique functional properties and potential physiological benefits. Different digestibility rates of food after ingestion are usually related to various physiological functions, and thus it causes different health effects, such as lowering the glycaemic and insulinemic responses to food, hypocholesterolemic action, and protective effect against colorectal cancer. Food products fortified with RS are becoming popular among consumers who are even ready to pay more for products enriched with RS to increase their dietary fibre intake.

The presence of RS in food is generally low, and it is determined by the starch botanical source, the condition of processing, and storage. The formation of RS during processing of carbohydrate-rich food is influenced by a few factors including moisture content, heating time and temperature, number of heating and cooling cycles, pH, freezing, and drying. RS type 3 is stable to thermal and often used as a functional ingredient in a wide variety of food products. Due to the good functional properties of RS, with no negative effects on the texture and taste of the end product, it is often incorporated into food products. Food products supplemented with RS has more palatability and greater consumer acceptability in terms of taste and colour than those of food products added with functional ingredients that are associated with high fibre content.

Exploiting fruits as well as its by-products, such as seeds, trunk, and peel, provides opportunity in its use as a natural resource of functional food ingredient in preparing value-added products. Therefore, this can benefit both local farmers and food as well as pharmaceutical industries. But associated drawbacks are related to consumer acceptability and processing/extraction cost concerns. Based on the information recorded in this review, it is expected that more botanical sources can be exploited for their potential as functional food ingredients (i.e. RS), including more food products fortified with RS that can be developed for local and international markets. Therefore, researchers and nutritionists should work together on RS production from different botanical sources as well as the application of this processed RS in the development of carbohydrate-based functional foods with low GI.

Acknowledgements

The authors wish to thank Universiti Sultan Zainal Abidin for the financial support from the University Research Grant under the Lab Material (LABMAT) 2018 grant (UniSZA/LABMAT/2018/02; R0044-R002).

Conflict of interest

All authors declare there is no conflict of interest in this review.

Notes

This review is submitted in partial fulfilment of the requirements for the LABMAT 2018 grant (UniSZA/LABMAT/2018/02; R0044-R002) publication.

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