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CRITICAL REVIEWS IN FOOD SCIENCE AND NUTRITION
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REVIEW

Impact of processing techniques on the glycemic index of rice

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ABSTRACT
Rice is an important starchy staple food and generally, rice varieties are known to have a higher glycemic index (GI). Over the years, the significance of GI on human health is being better understood and is known to be associated with several lifestyle disorders. Apart from the intrinsic characteristics of rice, different food processing techniques are known to have implications on the GI of rice. This work details the effect of domestic and industrial-level processing techniques on the GI of rice by providing an understanding of the resulting physicochemical changes. An attempt has been made to relate the process-dependent digestion behavior, which in turn reflects on the GI. The role of food constituents is elaborated and the various in vitro and in vivo approaches that have been used to determine the GI of foods are summarized. Considering the broader perspective, the effect of cooking methods and additives is explained. Given the significance of the cereal grain, this work concludes with the challenges and key thrust areas for future research.

KEYWORDS
Rice; glycemic index; processing; starch; digestion; in vitro; in vivo

Introduction

Rice (*Oryza sativa*) is a significant cereal crop with 95% of the global production from Asia. As a major staple food, it contributes to approximately 21, 14, and 2% of the world's energy, protein, fat supplies (Kennedy and Burlingame 2003) and is also a good source of micronutrients (Bodie et al. 2019). Over the years, numerous varieties of rice have been developed, aiming to provide the best yields and nutritional value, with high tolerance toward various biotic and abiotic factors. Rice kernels vary in geometry and can be grouped as long or short grains. In turn, their amylose contents can also vary (Kaur, Ranawana, and Henry 2016) which have predominant effects on cooking quality and consumption preferences. Harvested rice is referred to as rough rice or paddy and contains a caryopsis enclosed in the woody, siliceous hull, which is not edible. The hull is made up of palea and larger lemma and is further subdivided into four layers, protecting the caryopsis and grain. The primary edible component is the endosperm, which is a nutrient tissue that can grow into a next-generation plant. The endosperm also holds other outer layers such as the pericarp, testa, nucellus, and aleurone (Figure 1). Several research works have reported the health benefits, role of processing, nutritional aspects, value addition, storage quality and various other aspects of the post-harvest life of rice.

One important aspect associated with the consumption of rice is its high starch content ($75-80\%$) (Verma and Srivastav 2017). While this serves as the dietary carbohydrate source for millions across the world, the consumption of white rice is associated with a rise in the blood glucose responses; high glycemic load (GL) which is linked with the incidence of type II diabetes mellitus (Kempner, Peschel, and Schlayer 1958). The GI of rice can differ significantly depending on the starch ratio, i.e. amylose: amylopectin (Juliano and Goddard 1986).

The concept of GI has been used to explain the effect of starch and sugar-rich foods on the postprandial blood glucose response (Wolever et al. 2003) and is defined as the incremental area under the blood glucose curve after eating a test food containing 50 g of carbohydrates against a reference food having the same carbohydrate content (white bread and glucose are the common reference foods). The digestion behavior of carbohydrate-rich foods depends on various factors including the carbohydrate content, nature of sugars, cooking methods, processing, and presence of other food components. Based on GI values, foods can be classified into three types: low GI foods (GI <55), medium GI foods (GI $\sim$ 56 to 69), and high GI foods (GI $>$ 70) (Sethupathy et al. 2020). Consumption of foods with low GI can result in a moderate elevation in blood glucose concentrations, thereby improving insulin sensitivity and preventing type II diabetes (Fitzgerald et al. 2011). The postprandial blood glucose response is affected not only by the ingested food's GI but also by the amount of carbohydrates in it and hence the idea of GL came into use. GL is calculated as a product of GI and the total available carbohydrates of the test food. Based on GL, foods are classified as low (GL $\leq$ 10), medium (GL >10 - <20), and high (GL ≥ 20) (Sethupathy et al. 2020). For diabetics, consumption of low GI and low GL foods is recommended because of the

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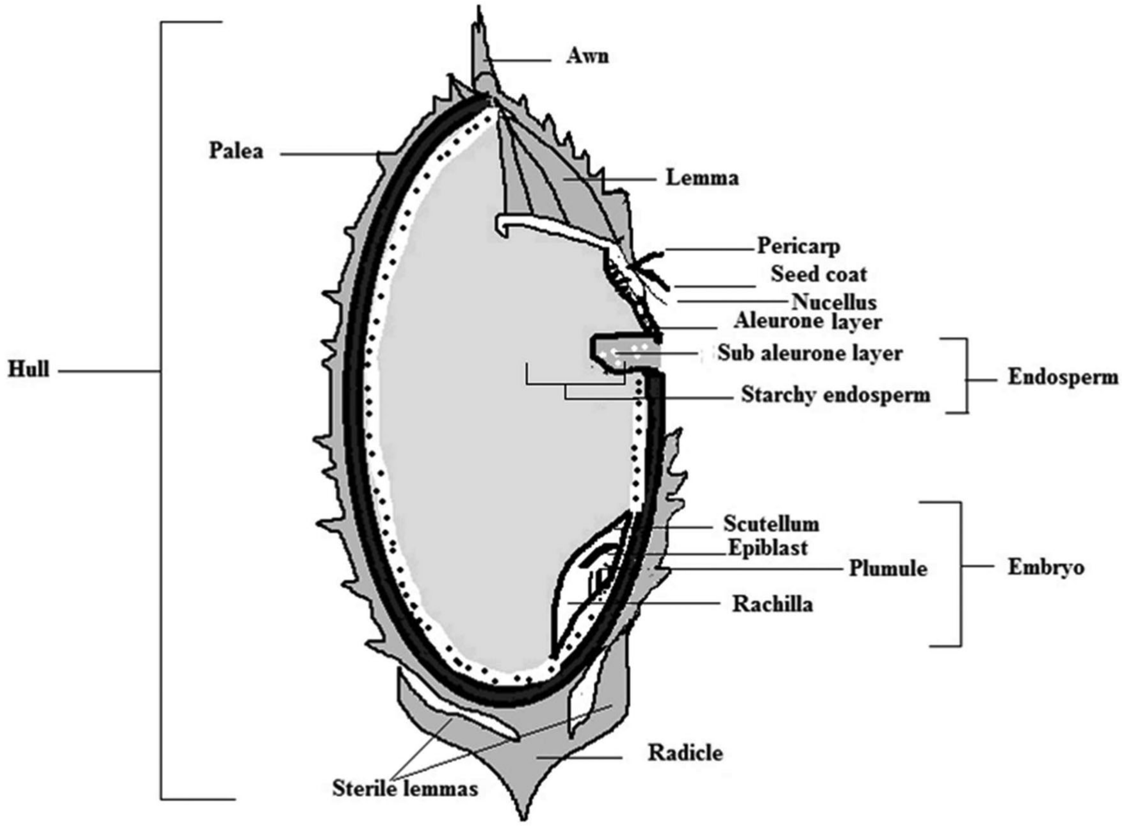

Figure 1. Structure of paddy.

impaired glucose metabolism during the postprandial phase. Thus, GI and GL are considered as critical parameters for choosing the diets for diabetic populations (Riccardi, Rivellese, and Giacco 2008).

Other than its amylose content, proteins, dietary fiber, and lipid contents also influence the GI. Apart from the impact of nutritional composition, rice processing methods can also affect the GI of rice (Boers, Seijen ten Hoorn, and Mela 2015). However, as of date, there is no detailed review on this aspect and the objective of this work is to address this requirement. This is because of the growing need to develop healthy food formulations and opt for healthier diets.

Understanding the digestion process and GI measurement

The digestion process is better explained when studied in vivo (using experiments performed within the living). However, the approach is challenging in terms of ethical aspects, complexity, and tediousness. Accordingly, various digestion models have been developed to imitate the human gastrointestinal tract for in vitro studies (experiments carried out in laboratory dishes).

In vitro methods

Approaches for in vitro digestibility of starchy foods are categorized into two types: (1) the unrestricted method in which laboratory dishes are used for food mixing and digestion, and (2) the restricted method in which a dialysis membrane-based approach is used for analyzing the in vitro glucose release behavior. While Englyst, Kingman, and Cummings (1992), Goñi, Garcia-Alonso, and Saura-Calixto (1997), Mishra, Monro, and Hedderley (2008), and Muir and O'Dea (1992) have reported the former approach, Brennan et al. (1996), Brighenti et al. (1995), Granfeldt et al. (1992), and Jenkins et al. (1984) have used the latter approach.

The interest in developing in vitro methods for starch digestion began in the 1960s. The first trial for in vitro starch digestibility was conducted by Southgate (1969a, 1969b) reporting the measurement of available and unavailable carbohydrates in foods using pullulanase and amyloglucosidase enzymes. However, issues on the incomplete removal of starch from the test samples were evident. Later, Englyst, Wiggins, and Cummings (1982) developed an in vitro method involving the use of two different enzymes (α-amylase and pullulanase) for rapidly digestible starch (RDS) digestion and the remaining undigested starch was further treated with amyloglucosidase. In the same year, Jenkins et al. (1982) reported an in vitro assay with results compared with in vivo trials. Then, Berry (1986) explained an in vitro method for the digestion of resistant starch (RS) based on Englyst, Wiggins, and Cummings (1982) with some modifications to mimic the exact physiological process during digestion. In 1991, Granfeldt and Björck (1991) proposed an in vitro starch digestibility method considering all the three phases of digestion. Further, in 1992, Casiraghi, Brighenti, and Testolin (1992); Englyst, Kingman, and Cummings (1992); Muir and O'Dea (1992) proposed various methods for in vitro digestion of starch as alternative approaches to Jenkins et al. (1982). Later, Englyst et al. (1999)

updated their method with some improvements and explained that the rapidly available glucose (RAG) is an indicator of rapid digestion and absorption of starch in the small intestine, explaining its relationship with the rise in postprandial blood glucose levels. Further, Englyst et al. (2003) extended their investigations by correlating the chemical characteristics and carbohydrate digestibility of cereal products. Based on the results, these researchers explained that the idea of higher slowly available glucose (SAG) content can help to produce low GI foods. A detailed study on the various in vitro methods for starch digestion was reported by Woolnough et al. (2008). Sopade and Gidley (2009) proposed a rapid glucometry in vitro digestion method in which pancreatic ɑ-amylase, pepsin, pancreatin and amyloglucosidase are used. In addition, the glucose concentration of samples was measured using a glucometer and the method was found to be sensitive, inexpensive and convenient to use. Dartois et al. (2010) proposed an in vitro method for waxy maize starch in which pepsin, pancreatin, invertase, and amyloglucosidase are used during the gastric and intestinal phases of digestion. Kumar, Sahoo, Baisakha et al. (2018) and Santhi Rajkumar et al. (2020) proposed alternative procedures to determine GI of foods in which the researchers used dialysis tube and bag, respectively, to mimic the small intestinal phase of digestion. Recently, Fernandes et al. (2020) studied the application of INFOGEST protocol in the determination of GI of rice in line with Minekus et al. (2014). A summary of all these approaches are presented in Table 1.

Dynamic in vitro methods

Models of in vitro dynamic digestion have gained significance as they require lesser time than in vivo research and can provide reliable results. As an advancement to in vitro methods of digestion, the dynamic gastric model (DGM) was developed by Wickham et al. (2012) (Figure 2a). Diverse works have been done using the DGM to assess nutrient release from the food matrices (Mandalari et al. 2010). Ballance et al. (2013) used the DGM for starch digestion. Kong and Singh (2008) developed an in vitro stomach model in the form of a jacketed vessel made up of glass to replicate the repetitive forces of contraction that are involved in the stomach. Later, Kong and Singh (2010) developed a human gastric simulator to replicate the peristaltic stomach movements during in vivo observations (Figure 2b) and its efficiency was evaluated by digesting apple slices and rice. Chen, Wu, and Chen (2013) developed a dynamic in vitro rat stomach model that mimicked the physiological and biochemical aspects of the human stomach. They compared the digestion behavior with in vivo experimentation in the rats. Subsequently, Chen et al. (2016) developed an advanced dynamic in vitro human stomach model in which starch hydrolysis of cooked white and brown rice were studied. Further, Wang et al. (2019) developed an advanced near-real dynamic in vitro human stomach system to study the digestion of beef stews and cooked rice and this model could reproduce in vivo gastric secretions and gastric emptying.

These models consider only the gastric phase of digestion. Therefore, to mimic the intestinal phase of digestion, Wright et al. (2016) developed a human duodenum model in the shape of a sigmoid to resemble the actual shape of the duodenum region. Parthasarathi, Bhushani, and Anandharamakrishnan (2018) developed an engineered small intestinal system (Figure 2c) consisting of 14 cm long perfusion chambers; during the study, a small intestine from a male Wistar rat is fixed within the perfusion chambers. To

Table 1. A summary of various in vitro starch digestion methods to determine GI of rice and other foods.

Type of food	Enzymes used	Results	References
Starch-based foods	Pepsin, pancreatin, amyloglucosidase, and invertase	RAG and SAG were found to a good indicator for the glycemic response of foods	(Englyst et al. 1999)
Starchy foods like cereals, rice, spaghetti, biscuits, etc.	Pepsin, α - amylase, and amyloglucosidase	*In vitro* and *in vivo* studies showed a good correlation. The equation for determining the GI of foods was given.	(Goñi, Garcia-Alonso, and Saura-Calixto 1997)
Cereal products	Pepsin, pancreatin, amyloglucosidase, and invertase	GI and insulinemic index were determined	(Englyst et al. 2003)
Indigenous rice varieties with varying amylose contents	Pepsin, α- amylase, and amyloglucosidase	The GI of different rice varieties showed significant variations	(Frei, Siddhuraju, and Becker 2003)
Rice noodles	Artificial saliva containing α- amylase, pepsin, pancreatin, and amyloglucosidase	Non-resistant starch, resistant starch, and GI was measured	(Srikaeo and Sangkhiaw 2014)
Polished rice	Pepsin, pancreatin	No morphological changes in rice were observed during both gastric and intestinal digestions	(Tamura et al. 2016)
Rice	Artificial saliva containing pancreatic α- amylase, pepsin, pancreatin, and amyloglucosidase	The starch hydrolysis was found to be 78.05–85.94%	(Kuang et al. 2016)
Bread, pasta, and cookies	INFOGEST protocol	Starch hydrolysis, different starch fractions (RDS, SDS, RS), and GI were determined	(Bustos et al. 2017)
Rice	INFOGEST protocol	Starch hydrolysis, different starch fractions (RDS, SDS, RS), and GI were measured	(Azizi et al. 2019)

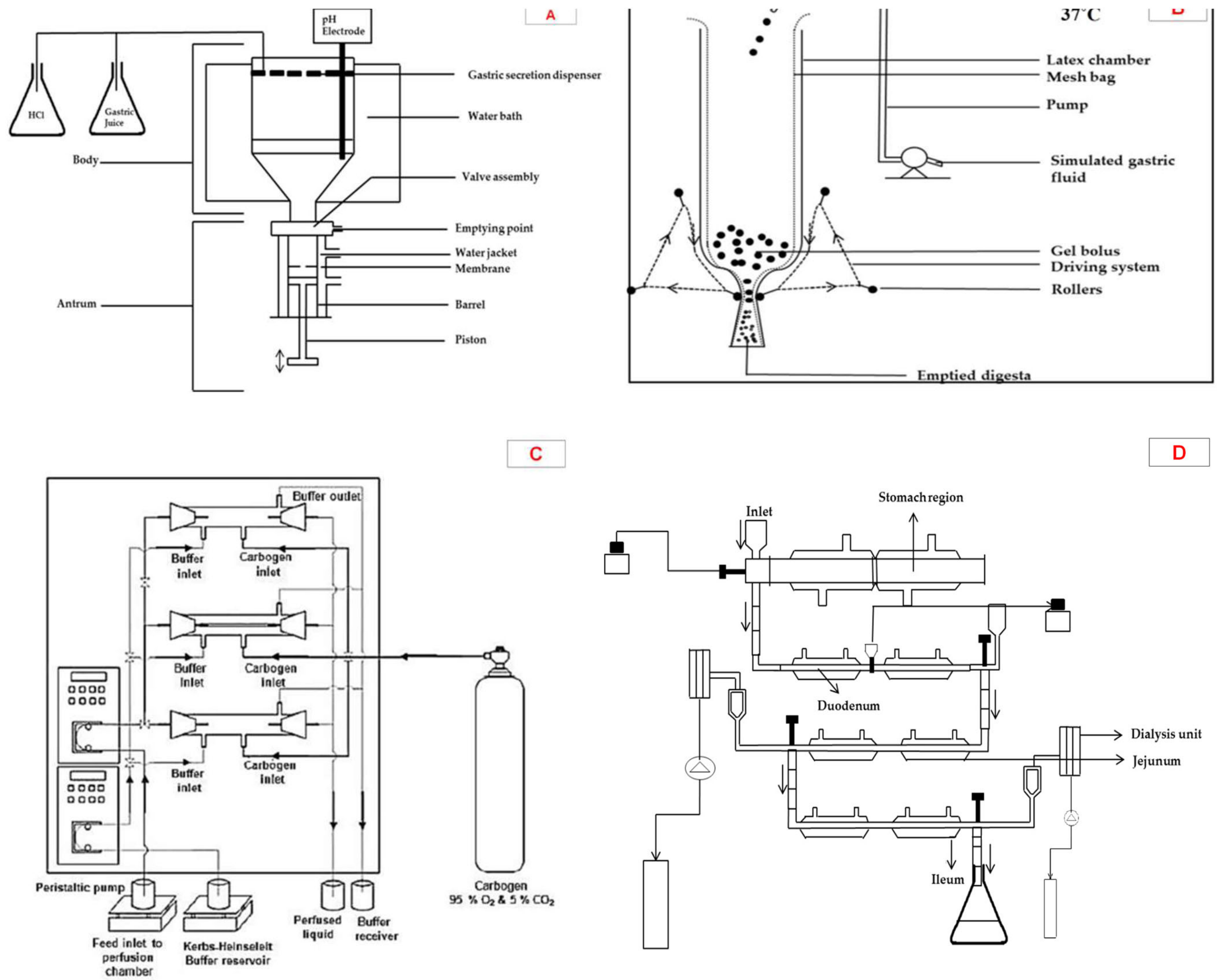

Figure 2. Examples of dynamic in vitro digestion models: (a) dynamic gastric model, (reproduced from Guerra et al. 2012 with permission from Elsevier); (b) human gastric simulator, (reproduced from Ye et al. 2019 with modifications and permission from Elsevier ; (c) engineered small intestinal system, (reproduced from Parthasarathi, Bhushani, and Anandharamakrishnan 2018 with permission from Elsevier); (d) TIM -1 (TNO gastrointestinal model) (reproduced from Mans Minekus, 2015 with modifications and permission from Springer Nature).

simulate both the gastric and intestinal digestion of foods, models such as those developed Mainville, Arcand, and Farnworth (2005) and the multicompartmental dynamic model are examples (Minekus et al. 1995) (Figure 2d). Bellmann et al. (2018) used the TNO (gastrointestinal) model to study the glycemic response of several carbohydrate foods. Similarly, Karthikeyan et al. (2019) used TNO's intestinal model 1 (TIM 1) to study the effect of bolus viscosity on the digestion of carbohydrates and glucose release. Nevertheless, overall, only limited studies report a detailed understanding of the GI of foods.

In vivo methods

In vitro methods of GI measurement do not consider the physiological processes of digestion. For instance, gastric emptying is a crucial factor that influences the rate at which food is available for digestion in the small intestine; various in vitro methods fail to consider this parameter. Further, the effect of meal viscosity on the absorption behavior during digestion is not considered during in vitro studies.

The concept of classifying foods based on their carbohydrate content and the subsequent effect on postprandial blood glucose was first introduced by Jenkins et al. (1981). Different in vivo tests have been performed for determining the GI of foods, including the method given by FAO/WHO (FAO/WHO 1998). Wolever et al. (2003) conducted an in vivo interlaboratory study to determine the GI of different foods. The study results indicated no variations between locations but showed significant variations between subjects. The GI of some of the common foods has been reported differently by different researchers owing to variations in the structural digestibility of starch and the choice of digestion protocols used. Given these differences, Arvidsson-Lenner et al. (2004) explained important considerations for in vivo determination of GI of foods (Table.2). In general, the in vivo method considers the ratio of area under the curve (AUC) of the blood glucose curve of the test food and the AUC of the reference food. The AUC of the blood glucose

Table 2. Important considerations for in vivo determination of GI of foods (reproduced from Arvidsson-lenner et al., 2004 with modifications and permission from Taylor & Francis Online).

Parameter	Considerations
The physical state of subjects	Healthy or diabetic
Number of subjects	Greater than 10
Duration of study	Morning
Background diet	Overnight fasting by the volunteers
Sample size	Serving size containing 50 g carbohydrates
Reference food	White bread or glucose
Blood sampling method	Venous or capillary method
Calculation	Considering 2 h blood glucose values

curve can be determined using different calculations: (1) total AUC, (2) incremental AUC_{cut}, (3) incremental AUC (IAUC), (4) incremental AUC_{min}, and (5) net incremental AUC (using trapezoid rule) (Figure 3).

Role of the composition of rice

A detailed understanding of the composition of rice (varieties) can help to explain its role in variations in functional characteristics, digestion behavior, and blood glucose response following consumption. Typically, the major nutrient constituents of rice are carbohydrates (80%), protein (7-8%), fat (3%), and fiber (3%) (Juliano 1985). The positive relationship between GI and consumption of carbohydrates-rich foods is well documented (Nanri et al. 2010). Nonetheless, the impact of individual nutrients and overall composition on the GI of rice needs to be studied in-depth.

Starch

In general, the starch molecules of rice are smaller ($3-9\,\mu m$) than other starch molecules that have increased surface to volume ratio, and hence their rate of digestibility is higher (Wang et al. 2017). Gallant, Bouchet, and Baldwin (1997) reported that rice starch has peripheral pores linked to internal channels which have an 'inside out' digestibility pattern with a higher rate of hydrolysis unlike starch molecules of potato and high amylose maize starches that have an 'outside-in' pattern that is difficult to digest. Further, the crystalline pattern of the starch molecule also affects the rice GI. Rice starch is thermally stable with a crystalline pattern of type A. On the other hand, the crystalline pattern of type B is arranged in a double-helical hexagonally packaged structure. The crystalline pattern type C is a mixture of types A and B (Toutounji et al. 2019). Zhang, Venkatachalam, and Hamaker (2006) reported that rice starch with crystalline pattern A-type is highly accessible to enzymatic hydrolysis, as it has three times higher RDS than the B-type. Besides, Butardo et al. (2011) stated that changes in the white rice crystalline pattern from A-type to B and C during in vitro digestion have reduced the rate of enzymatic hydrolysis. This was because, the B-type crystalline pattern starch has a higher proportion of long-chain amylopectin with a stable double-helical structure, higher gelatinization temperature, stringer crystalline nature and is thus less susceptible to hydrolysis during digestion (Wang et al. 2017; Butardo et al. 2011).

Starch is the major component of rice and directly influences its GI. It can be available in the form of RDS, slowly digestible starch (SDS), and RS. The RDS (digestion within 20 minutes) causes the blood glucose level to increase quickly, SDS (20-120 min digestion) undergoes lower digestion in the small intestine, and RS is the indigestible portion (digestion beyond 120 min) of starch fermented in the large intestine and can help in the management of diabetes by controlling the GI (Giri et al. 2017). Enzymatic digestion of rice depends on the composition of two different polysaccharides of the starch molecule: amylose and amylopectin. Amylose is a linear molecule comprising of α (1-4) bonds and amylopectin is a highly branched glucan with α (1-4) bonds linked with α (1-6) bonds. Rice with higher amylose content has been reported to gradually increase blood glucose levels than rice with higher amylopectin content. This is because the structure of amylose is very hard to disintegrate during digestion. Zhu et al. (2011) explained that amylose molecules may initially be hydrolyzed by the amylase enzyme and these hydrolyzed molecules may re-associate and resist digestion. Guzman et al. (2017) reported that rice with higher amylose content and RS would have a lower GI. Moreover, the study highlighted that a higher level of long-chain amylose or long-chain amylopectin that behaves like amylose may lower the GI of rice. Further, Kumar, Sahoo, Baisakha et al. (2018) emphasized the positive correlation between RS and amylose contents of rice, which form type-V RS (amylose-lipid complex) resulting in low GI. Trinidad et al. (2013) observed lower GI for milled rice with higher amylose content than brown rice. However, several studies have also highlighted that the amylose content of rice has no relationship with RDS or the rate of digestion (Cai et al. 2015; Dhital et al. 2015). Lin et al. (2018) explained that only the amylose, and the structure of amylopectin do not play a significant role in the rice of GI. Therefore, long-chain amylopectin, which mimics the amylose structure and function, may increase the RS content and thus reduce the GI (Butardo et al. 2011, 2017).

Fiber

The presence of viscous and dietary fiber (DF) thickens the food blend in the digestive tract and slows down the action of digestive enzymes on food. After cooking, amylose can be easily staled and is metabolized in a similar way as dietary fiber (Chang et al. 2014). Foster-Powell, Holt, and Brand-Miller (2002) quantified the combined effects of amylose and DF in lowering the rice GI. Among the different rice fractions, brown rice consists of more insoluble fiber that can reduce the risk of type II diabetes. Brown rice can result in low glycemic response when consumed as a whole grain, and also contains various micro and phyto nutrients (Ley et al. 2014). Brown rice exhibits longer cooking times and lesser gelatinization, in turn slowing down the digestibility of starch in the small intestine (Ruchi et al. 2014). However, consumer awareness and preferences for brown rice are relatively low; brown rice is characteristic of lesser shelf-life and poor sensorial attributes than white rice (Sudha et al. 2013).

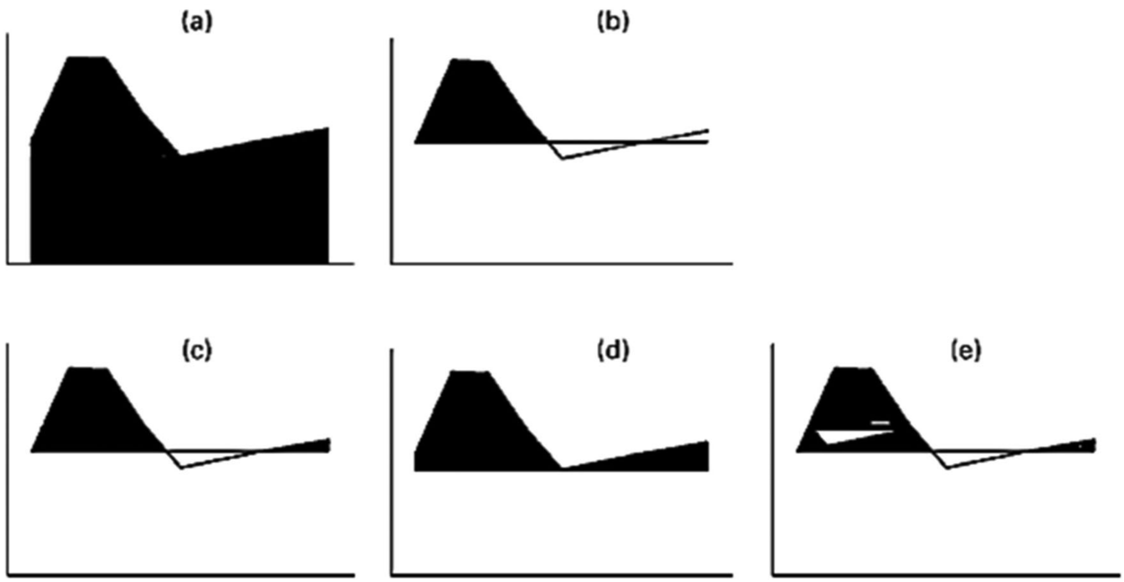

Figure 3. Different approaches for AUC measurement for in vivo studies:(a) total AUC, (b) $IAUC_{cut}$, (c) IAUC, (d) $IAUC_{min}$, (e) net AUC.(reproduced from Brouns et al., 2005 with permission from Cambridge University Press).

Proteins and lipids

Lipids are found majorly in rice embryo and aleuronic layer (Toutounji et al. 2019), and can also alter the GI. Holm et al. (1983), Goddard, Young, and Marcus (1984); Shu et al. (2009) reported that the complex developed between starch and lipid during cooking is type 5 RS (amylose-lipid complex), which may be the contributing factor in reducing the GI of higher amylose rice. Similarly, Smart et al. (2013) found that fat-rich meals can reduce blood glucose response as the long-chain saturated monoglycerides are highly resistant to enzymatic digestion than the short-chain (saturated and unsaturated) monoglycerides (Guraya, Kadan, and Champagne 1997). Further, Ye et al. (2018) also studied rice flour's starch digestibility in the presence and absence of lipids, and the results suggested that the presence of lipids could reduce GI.

The degree of cereal starch digestibility also depends on protein-starch interactions (Wong et al. 2009). In a study conducted by Ye et al. (2018), the digestibility of starch was found to increase in the absence of protein. This was because the interaction between endogenous protein and starch decreased in the absence of protein, enabling the starch to be hydrolyzed by the digestive enzymes. Some clinical studies have also suggested that the absence of protein could increase the starch hydrolysis in cereals and thus increase GI (López-Barón et al. 2017). Also, it was observed that the presence of protein molecules may induce the formation of the amylose-lipid complex (Chao et al. 2018). Besides, Sugiyama et al. (2003) reported that consumption of carbohydrate-rich foods along with proteins may reduce its GI as it promotes insulin secretion. Also, Zhu et al. (2011) observed a negative correlation between rice flour protein and RDS and SDS, and a positive correlation with RS content.

Starch-lipid interactions

Starch-lipid complex refers to the incorporation of lipid molecules into amylose (Figure 4) (Putseys, Lamberts, and Delcour 2010) and its formation affects the characteristics of starch and its digestibility. This is evident in native and processed starch granules during the heating or cooling stages of food processing(Wang, Chao, et al. 2020). The melting temperature of the starch-lipid complex is greater than 100 °C; hence, it is not melted during the cooking process. During the formation and stabilization of the starch-lipid complex, non-covalent interactions, hydrophobic attraction, and van der Waals forces occur (Putseys, Lamberts, and Delcour 2010). The amylose molecules of starch are primarily responsible for forming a complex with lipid (type-V RS) than the highly branched amylopectin (Ai, Hasjim, and Jane 2013). Rice starch exhibits characteristic rheological behavior and has been explored for food 3D printing applications (Theagarajan, Moses, and Anandharamakrishnan 2020). In a recent study, the 3D extrusion printability of egg fractions was improved using rice flour (Anukiruthika, Moses, and Anandharamakrishnan 2020). These researchers explained the prospects of rice constituents in developing customized foods.

The starch-lipid complex forms an insoluble film on the starch granules which is highly resistant to digestion (Tester and Morrison 1990). This is because the amylose and amylopectin molecules are capable of forming a helical complex with fatty acids and fatty alcohols during the complex development, in turn, restricting amylase from cleaving it. Also, the complex can intertwine the long-chain amylopectin molecules, thereby resulting its enzymatic hydrolysis (Hasjim et al. 2010; Seneviratne and Biliaderis 1991). Similarly, Hasjim, Ai, & Jane (2013) reported that the starch-lipid complex is highly resistant to enzymatic hydrolysis during digestion may be due to its collapsed helical structure that prevents the binding of enzymes with the amylose molecules (Jane and Robyt 1984). Besides, the starch-lipid complex influences the binding ability of amylolytic enzymes due to helical modifications within the amylose molecules (Annor et al. 2015). Also, the starch-lipid

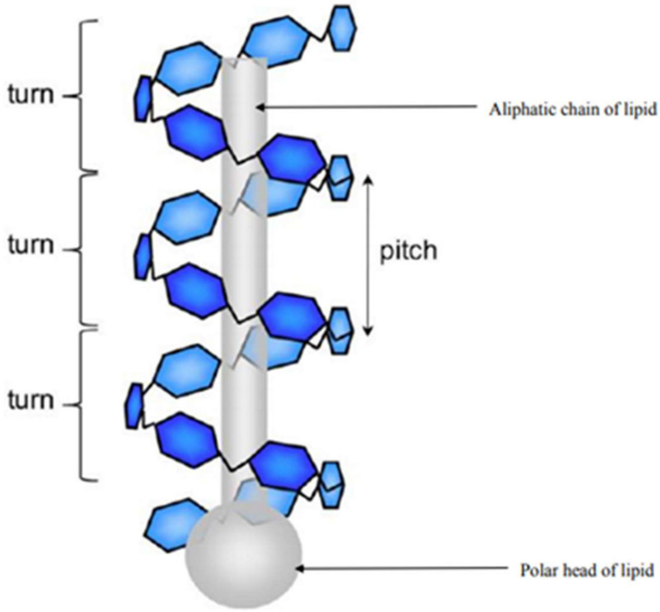

Figure 4. Schematic representation of starch-lipid complex formation. (reproduced from Putseys et al., 2010 with permission from Elsevier).

complex enhances the entanglement of resistant starch between amylose and amylopectin, and thus the enzyme accessibility to hydrolyze the starch is reduced (Becker, Hill, and Mitchell 2001; Cui and Oates 1999). X-ray diffraction (XRD) patterns explain that the crystalline pattern of the starch-lipid complex is of V type, indicating lesser extents of starch digestion. Therefore, the complex between starch and lipid during food processing may reduce the GI (Wang, Chao, et al. 2020).

Effect of processing methods involved in the production of rice for direct consumption

Different food processing techniques have been used and these can modify the digestibility of starch and have implications on the GI. Based on the type of processing, gelatinization, and retrogradation of starch occur influencing the formation of resistant starch. Though post-harvest processing of rice affects the overall nutritional characteristics of rice, its effect on the postprandial blood glucose response remains unclear.

Parboiling (soaking, steaming, and drying)

Parboiling is one of the important unit operations in the paddy processing supply chain. It is reported that around 60% of the rice produced in some countries is parboiled. Parboiling is a hydrothermal process in which swelling of starch granules, denaturation of protein bodies, and lipid-amylose complex formation occur (Priya et al. 2019). A typical paddy parboiling process involves (1) soaking (hydration) - steeping at $60-70\,°C$ for $4-6\,h$ (grains with or without hull), (2) steaming at $100-110\,°C$ for $10-20\,min$, (3) drying, and (4) removal of the hull, if required (Carvalho et al. 2018). Soaking is the primary stage and may alter the composition and distribution of nutrients within the grain (Mir, Bosco, and Sunooj 2013; Sareepuang et al. 2008). During the soaking of paddy, the grain gets hydrated of and the moisture content increases to $40-45\%$ (Bhattacharya and Juliano 1985), sufficient for subsequent starch gelatinization. Gelatinization refers to the structural breakdown of hydrogen bonds within the starch granule that occurs during hydrothermal treatment, resulting in irreversible changes and gelatinized starch is susceptible to digestion by digestive enzymes. Also, during soaking, leaching of rice constituents into the soaking water occurs (Sareepuang et al. 2008). Generally, during soaking, the water temperature is maintained less than the gelatinization temperature (GT) of rice starch and thus complete gelatinization takes place during the steaming stage of parboiling. The GT of rice ranges between 55 and 79 °C and varies among the cultivars. The heating stage of parboiling allows the transfer of micronutrients due to diffusion from the aleurone and germ layer to the starchy endosperm. Retrogradation of rice starch takes place after steaming and continues until milling. This phenomenon explains the restoration of the amorphous structures of the gelatinized rice, making it difficult to digest. After steaming, drying is carried out to bring down the moisture content to around 14-16% to attain the desirable milling properties. The high-temperature process of parboiling may impair the natural antioxidants of rice that prevent rancidity reactions. Also, improper drying of parboiled rice may result in mold growth (Atungulu and Pan 2014) and subsequent mycotoxin production (Moses, Jayas, and Alagusundaram 2015).

The effect of soaking duration, temperature, and soaking medium on the quality of parboiled rice and GI has been discussed by various researchers. Miah et al. (2002) conducted experiments to study the effect of hot soaking on the degree of starch gelatinization. Hot soaking of paddy was performed at 80°C for 15, 30, 45, 60, 120 min and samples soaked for 120 min exhibited a higher degree of gelatinization. Han and Lim (2009) soaked brown rice kernels at 25 and 50°C and the soaked kernels were cooked in the soaked water and distilled water. The kernels cooked in soaked water had lower GI than those cooked in distilled water as the leached solids interacted with the rice kernels, resulting in a tougher texture with higher SDS and RS contents. Besides, higher soaking temperature and soaking time can induce more leaching of carbohydrates. These researchers also reported that amylose leached in the soaked water would easily retrograde when the cooked rice is cooled, thus providing a protective layer that can reduce the GI. Kale et al. (2015) studied the influence of soaking conditions on the GI of basmati rice by varying soaking temperatures between 40 to 80°C. They reported decreased crude protein, starch, and amylose contents after soaking due to the leaching of solids in the soaking medium. Also, the rate of leaching of solids was more at higher soaking temperatures. On the contrary, because of the diffusion of fat globules into the starchy endosperm, the crude fat and the fiber content of soaked rice were higher than the unsoaked counterpart. Further, leaching of amylose and the formation of the

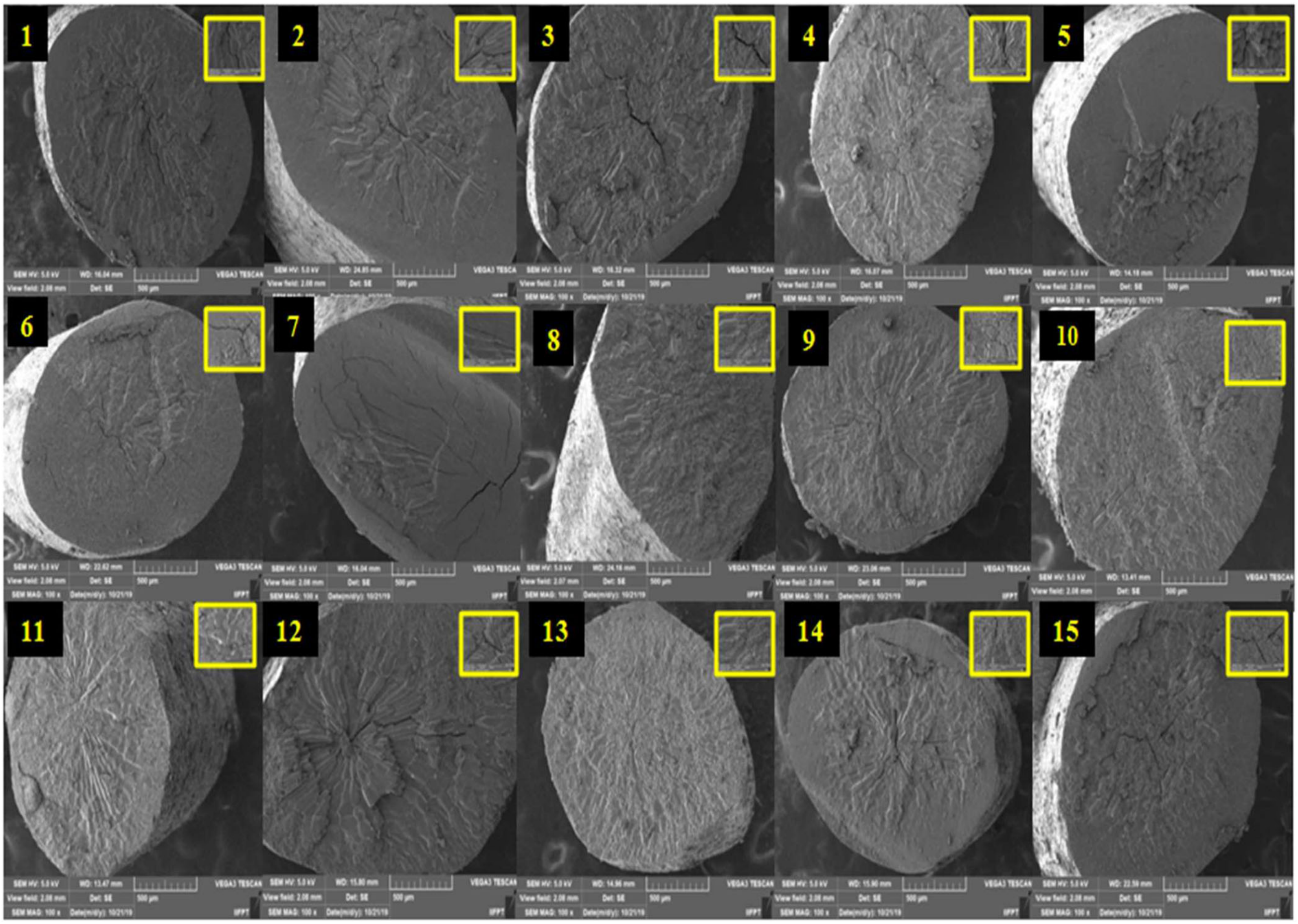

Figure 5. Morphological changes of rice before and after parboiling: Raw rice samples with cracks on the surface (1-5), Pressure parboiled (6-10), and Parboiled by open steaming (11-15). (reproduced from Sivakamasundari, Moses, and Anandharamakrishnan 2020 with permission from Springer).

amylose-lipid complex during soaking at higher temperature can reduce the amylose: amylopectin ratio. A decrease in the GI of basmati rice was reported when the rice kernels were soaked at a temperature of $\geq$ 60°C. This implies that soaking rice at higher temperatures for a short duration or low temperatures for a longer duration can change the physicochemical properties and alter the GI (Purohit and Rao 2017). Nawaz et al. (2018) used various soaking mediums (water, 3% NaCl, 0.2% acetic acid) for the parboiling process. A substantial decrease in sample crystallinity soaked in NaCl and acetic acid was reported, explaining a decrease in the degree of starch digestibility. However, in the study, the GI of the samples soaked in saline was higher than water-soaked samples owing to the stimulated activity of the α-amylase enzyme in the presence of salt (Nawaz et al. 2018).

Besides soaking, the steaming process plays a crucial role in altering the GI during the parboiling process. Dutta and Mahanta (2012) studied the impact of open steaming (for 10, 15, and 20 min) and pressure steaming (15 psi for 10, 15, and 20 min) on rice varieties with varying amylose contents. For pressure-parboiled samples, with increased equilibrium moisture content, the degree of gelatinization was found to be higher than samples processed under open steaming. The study also reported a loss in crystallinity due to the increased water absorption during the parboiling process. The RS content of the samples reduced with the severity of processing owing to the breakdown of long-chain amylose. Besides, increased rice starch digestibility is evident during steaming due to the insufficient time between the gelatinization and drying stages that result in incomplete retrogradation of starch (Toutounji et al. 2019). Similarly, in a recent study Sivakamasundari, Moses, and Anandharamakrishnan (2020) reported reduced GI of rice that was pressure parboiling, in comparison with rice that was open steamed. The morphology of parboiled and non-parboiled rice samples is given in Figure 5, explaining the differences in the surface of parboiled rice (devoid of cracks and internal fissures), thus confirming the presence of pre-gelatinized starch after parboiling. Also, the study highlighted the inverse correlation between GI and amylose content for the selected rice varieties. Kale, Jha, et al. (2017) studied the effect of different steaming pressures (0–1.5 kg/cm^2) and steaming duration (5–25 min) on the GI of Pusa basmati rice and these results were contradictory with those reported by Dutta and Mahanta (2012). It was observed that the GI of rice was reduced ($<$ 55) with the severity of processing (1.5 kg/cm^2 for 20 min). Cheng, Chen, and Yeh (2018) studied the in vitro digestibility of rice during parboiling (pressure parboiling) and heat moisture treatment (HMT). In combination with HMT, pressure parboiling increased the RDS and

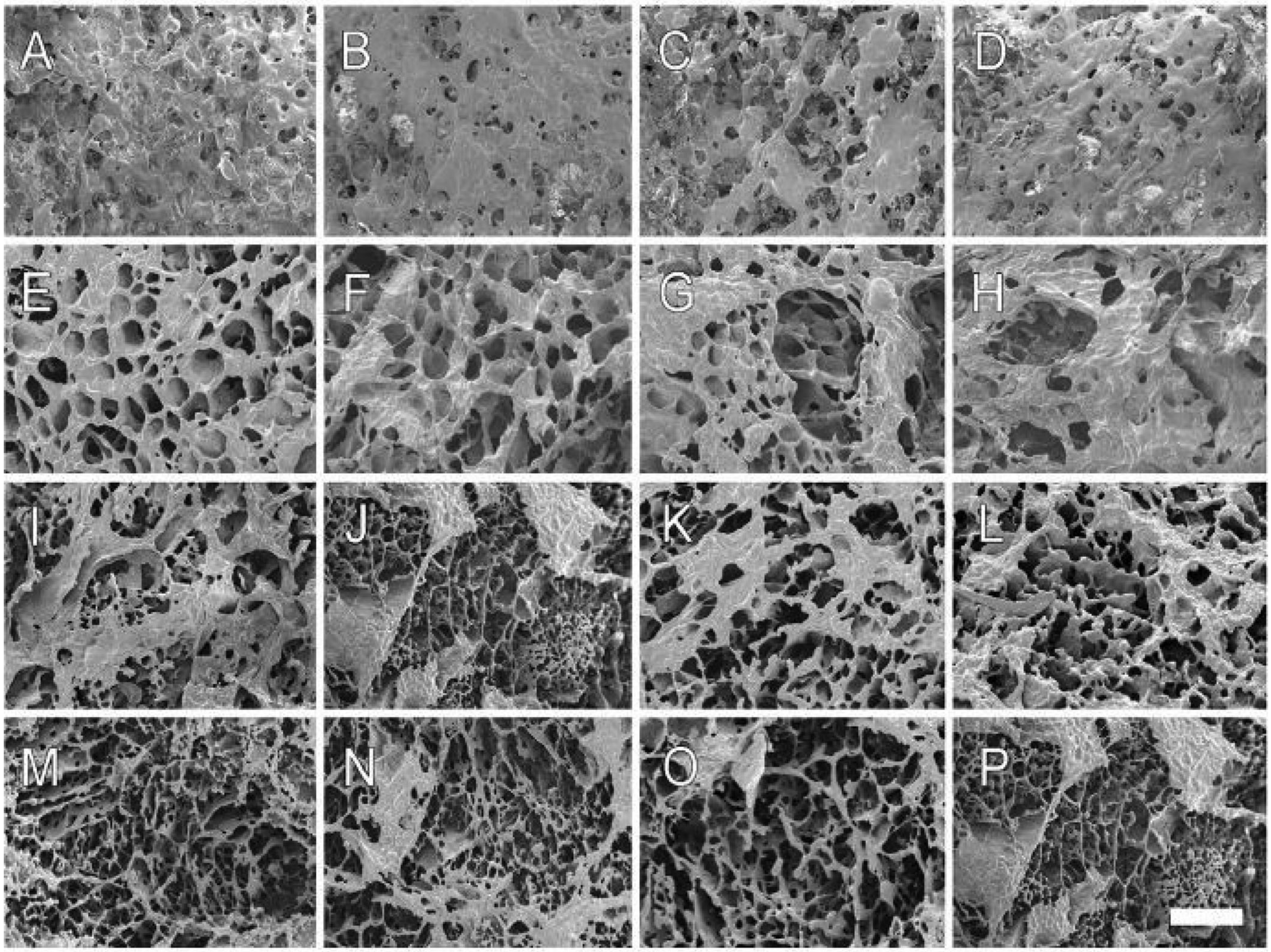

Figure 6. Microstructural changes of brown rice (a, e, i, m), polished rice (b, f, j, n), parboiled rice (c, g, k, o), and polished parboiled rice (d, h, l, p) during simulated gastric and small intestinal conditions. (reproduced from Tian et al. 2018 with permission from Elsevier).

SDS, thus reducing the GI of rice. Arns et al. (2014) and Chung, Liu, and Hoover (2009) reported that the amylose-lipid complex formation can result in the stabilization of SDS levels, with higher RS during HMT. Van Hung et al. (2020) also reported that HMT can minimize the GI as it increases the RS content. Kale, Kale, et al. (2017) studied the impact of parboiling (with different soaking and steaming steps) on starch digestibility and GI of PB1121basmati rice varieties. Reduction in starch hydrolysis, pasting viscosity, and the crystalline structure has been reported during soaking. On the other hand, complete starch gelatinization of rice starch was reported during the steaming of paddy; however, only partial starch gelatinization was reported during soaking and both processes reduced the GI of rice.

It was reported by Larsen et al. (2000) that parboiling reduces the GI to nearly 30% relative to the same variety's non-parboiled rice. Hamad, Zafar, and Sidhu (2018) also explained that parboiled rice may reduce the postprandial blood glucose response of diabetic individuals, and therefore can be used as an alternative for non-parboiled and brown rice. In a recent study by Tian et al. (2018), the in vitro digestibility of rice was found to reduce due to the parboiling process. These researchers also presented the microstructural changes of different rice fractions (brown rice, parboiled rice, polished rice) during in vitro digestion. The morphologies of brown rice and parboiled rice (Figure 6a-d) were reported to be different than the polished rice. Besides, rice digested in simulated gastric conditions (Figure 6e-h) had holes due to the digestion of protein molecules and leakage of starch into digestive medium which was gelatinized during cooking. Whereas, during the simulated small intestinal conditions (Figure 6i-p) more amorphous voids were observed, increasing with the extent of digestion. Also, Tian et al. (2018) reported that the presence of pericarp in brown rice and the retrograded amylopectin and amylose-lipid complex in the parboiled rice decreases the digestibility of starch.

The impact of post-harvest drying of paddy on the in vitro starch digestibility was studied by Donlao and Ogawa (2017) in which two different drying methods (hot air drying and sun drying) were used. Then, the paddy was milled and the rice was cooked using an electric cooker. It was observed that the GI of rice obtained after hot air drying at 115°C was higher as the high-temperature application had created internal fissures in the grain that facilitates higher enzymatic digestion. Nevertheless, the effect of other drying methods used during industry-scale processing of rice must be studied in detail. These would of particular interest for value-added products including quick-cooking rice and other ready-to-cook rice-based foods.

Milling and polishing

Post-harvest paddy processing includes the production of graded and polished white rice from the harvested paddy. The process of milling is also denoted as dehulling or shelling. During dehulling, various fractions like brown rice, hull, and dehulled rice are separated. The dehulled paddy is then milled or polished and raw white rice (head rice and broken) is produced, devoid of the lipid portion of the bran. Depending on the variety of rice and the degree of processing, the optimal milling operation will produce hull (20%), bran (8-12%), and milled rice or white rice (68-72%) at different levels. This is then packed and stored for further use (Sahay and Singh 1996). Milling of cereals may cause damage to the starch structure and based on the degree of damage, its water absorption capacity and degree of swelling may vary. Also, the damaged starch is more prone to enzymatic hydrolysis than intact starch granules (Tran et al. 2011).

The bran and cell wall of the endosperm in brown rice comprises of the non-starch polysaccharides that act as a barrier to the starchy endosperm. The bran layer is removed during polishing and any instability to the intact bran layer can increase the rate of starch digestibility as digestive enzymes can easily access the starchy matter (Shobana et al. 2017). Casiraghi et al. (1993) reported a higher GI for polished rice than parboiled and quick-cooking parboiled rice. Also, Karupaiah et al. (2011) observed a higher GI for polished rice as compared with unpolished brown rice. Shobana et al. (2011) studied the nutritional and sensory profile of brown rice and white rice (2.4, 4.4, and 8.0% of polishing), and significant variations in the protein, fat, dietary fiber, ɣ-oryzanol, polyphenols, and antioxidant activity was observed. Further, the available carbohydrate of white rice had increased with the degree of polishing and therefore could increase the GI. Trinidad et al. (2013) also concluded that the GI of brown rice was lesser than milled rice. Similarly, a decreased glycemic response for brown rice was reported by Mohan et al. (2014). Further, Shobana et al. (2016) determined the GI of Indian rice Bapatla – BPT-5204 under three different polishing conditions such as 0% polishing (parboiled brown rice), 2.3% polishing (under milled rice), and 9.7% polishing (white rice). The results of this study emphasized that brown rice had a lesser GI (∼57.6) than the undermilled (∼73) and white rice (∼79.6). Sasaki et al. (2016) compared the glucose release characteristics of brown rice, surface abraded brown rice and white rice. A higher rate of starch digestion was observed for white rice than brown rice. Somaratne et al. (2017) studied the effect of milling on the GI of red and white basmati rice. Though rice varieties were polished at two distinct levels (10 and 100%), the degree of polishing showed no significant effect on the GI; however, the dietary fiber content of the rice showed a negative correlation with GI as it slows down the action of digestive enzymes. Besides, the study reported that red basmati rice has higher antioxidant (AA) activity and this in turn has an inverse relationship with GI. Upon polishing, reduction in AA was observed in white rice (100% polished) than the 10% polished rice.

Effect of processing methods involved in the production of value-added products

Apart from consumption in the form of whole rice, around 10% of the total available rice is converted into different value-added products (Mishra, Nain, and Singh 2015). These techniques are known to significantly affect digestion behavior and GI of rice and are detailed in this section.

Germination

Germination is one of the inexpensive processing methods of rice which can improve its nutritional quality (Wu et al. 2013). Since brown rice has a very rich nutritional profile, its consumption is not very common as it is difficult to cook, digest, and has poor textural properties apart from challenges associated with long-term storage (Komatsuzaki et al. 2007). For producing germinated rice, brown rice is soaked in warm water at 35-40 °C for around10-12 h, and sprouts of length 0.5-1 mm can be obtained (Patil and Khan 2011). The germinated brown rice contains various nutrients like gamma-aminobutyric acid (GABA), phytic acid, tocotrienols, potassium, zinc, ɣ-oryzanol, and ferulic acid, most of which can be digested and absorbed easily (Moongngarm and Saetung 2010). During germination, the soak water must be changed every 3-4 h interval to prevent fermentation and maintain a constant temperature throughout the process.

Consumption of germinated brown rice is associated with several advantages for the diabetic population. Ito et al. (2005) reported that consumption of germinated brown rice reduces the postprandial blood glucose response in healthy subjects owing to the presence of high dietary fiber which restricts α-amylase digestion in the small intestine. Also, pre-germinated brown rice has GABA that can increase insulin levels (Gomez et al. 1999), apart from various bioactive compounds that can lower the GI. The effect of various drying temperatures on the GABA content of pre-germinated brown rice was studied by Chungcharoen et al. (2014). These researchers observed that the preparation of germinated rice from paddy (GP) was effective and had higher amounts of GABA dietary fiber and glucose than that from brown rice (GBR). Further, during drying, the loss of A-type crystalline pattern was higher in GP with a higher degree of starch gelatinization than GBR. In a recent study, Xia et al. (2020) used high-intensity ultrasound for pre-germinated rice. The rate of germination of rice was increased significantly within 5-30 min of ultrasound application, decreasing the starch content and increasing reducing sugar levels (Figure 7).

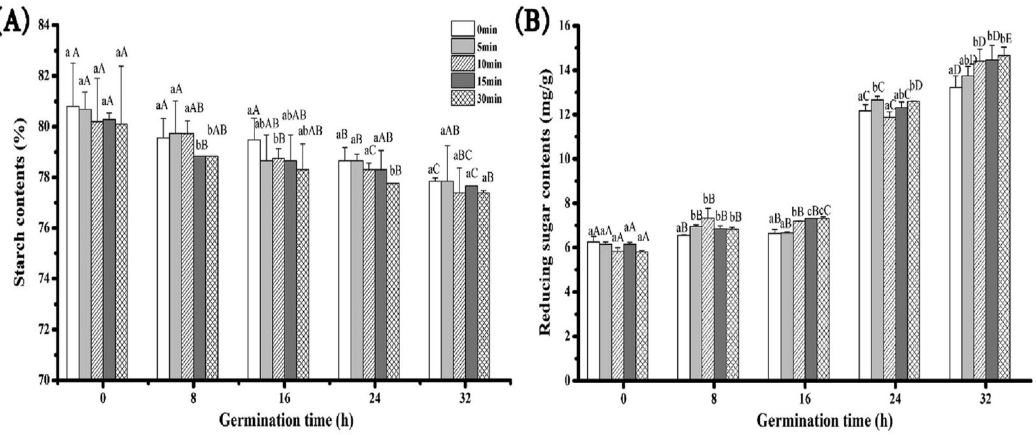

Figure 7. Changes in starch content (A) and reducing sugar (B) in the presence and absence of high-intensity ultrasound. (reproduced from Xia et al. 2020 with permission from Elsevier).

Puffing

Puffed rice is prepared from pre-gelatinized milled rice and contains 89% carbohydrates, 5-9% protein, and other nutrients like dietary fiber, phytochemicals, vitamins, and minerals. A typical process for the production of puffed rice includes parboiling, drying, milling, and roasting (Joshi et al. 2014). Rice with higher amylose content results in more expansion during puffing (Madhuri 2002) and thus *Indica* rice with medium and higher amylose contents (Juliano and Perdon 1975) can be puffed conveniently.

Puffed rice contains pre-gelatinized starch with a porous structure that is highly susceptible to enzymatic digestion (Mishra, Hardacre, and Monro 2012). Also, the application of higher temperature and pressure during puffing may result in a higher degree of gelatinization, in turn, creating more contact area for amylase to hydrolyze starch molecules (Van Hung, Chau, and Phi 2016). Wolever (1990) observed higher GI for puffed rice (132) than white rice (81) even though the available carbohydrates for digestion was higher for white rice. Similarly, higher GI was reported for puffed rice than rice flakes as parching of grains during puffing created some structural changes to the starch (Mani et al. 1994). During the in vitro digestion of puffed rice, Mahadevamma and Tharanathan (2007) observed damaged starch that can absorb more water and is highly susceptible to enzymatic digestion. Singhania and Sen Ray (2012) studied the in vivo glycemic response of puffed rice, kheer rice, and boiled rice. Among the rice products, the GI of puffed rice was higher as the high temperature during puffing had converted the starch into short-chain glucose units (dextrins) that are easily digested by the enzymes. In addition, the percentage of damaged starch was higher in puffed rice explaining higher amylolytic susceptibility. Kumar and Prasad (2018) confirmed the structural disintegration of compact starch during the puffing process using a scanning electron microscope. Similar to puffing, instanization of rice is also known to result in higher GI even in the high amylose varieties (Kaur, Ranawana, and Henry 2016).

Size reduction (flour milling)

Particle size reduction has significant implications on the physicochemical properties of rice(Prabhakaran and Moses 2016). The particle size of rice also influences the rate of starch digestibility both in vitro and in vivo. Booher et al. (1951) reported that rice with smaller particle size exhibits an increased rate of starch digestibility. A similar observation was reported by O'Dea, Nestel, and Antonoff (1980) where the GI of cooked grounded rice was higher than the whole grains in both healthy and diabetic subjects owing to the higher available surface area of starch for digestion. This was because the surface area exposed by the grains to the digestive enzymes would be higher with an increased rate of starch digestibility during size reduction (de la Hera, Gomez, and Rosell 2013). Similarly, the in vitro digestion of milled rice (waxy, white, black, and brown rice) with different size fractions was studied by Farooq et al. (2018). In the study, rice was hammer milled and the particles were categorized as coarse (300−450 µm), medium (150−300 µm), and fine size (<150 µm). The rate of starch digestion was found to be higher for fine particles than for the other two fractions. This is because an increase in particle size is associated with the rice flour's swelling power, solubility, and gelatinization temperature, all of which in turn relates to the digestibility (Farooq et al. 2018). Lee et al. (2019) studied the effect of jet milling and hammer milling on the in vitro starch digestibility of germinated brown rice powder. It was concluded that jet milling produced two different particle fractions (coarse and fine) with higher damaged starch (11.61 ± 0.18% and 11.33 ± 0.63%, respectively) and could be easily digested as compared with the hammer-milled samples (8.35 ± 0.70%).

Apart from the particle size, the microstructure of rice also influences the GI. Schwanz Goebel et al. (2019) studied the rate of starch digestibility for *Japonica* and *Indica* rice varieties. During simulated in vitro gastrointestinal digestion, the *Indica* rice maintained its compact structure until the middle phase of small intestinal digestion, resulted in a lower rate of starch hydrolysis than in the case of the *Japonica* variety. Also, higher levels of the lipid-amylose complex were found in the *Indica* rice, explaining slower starch digestibility.

Extrusion

Rice can be extruded to manufacture various new products such as modified starch-based snacks, precooked breakfast

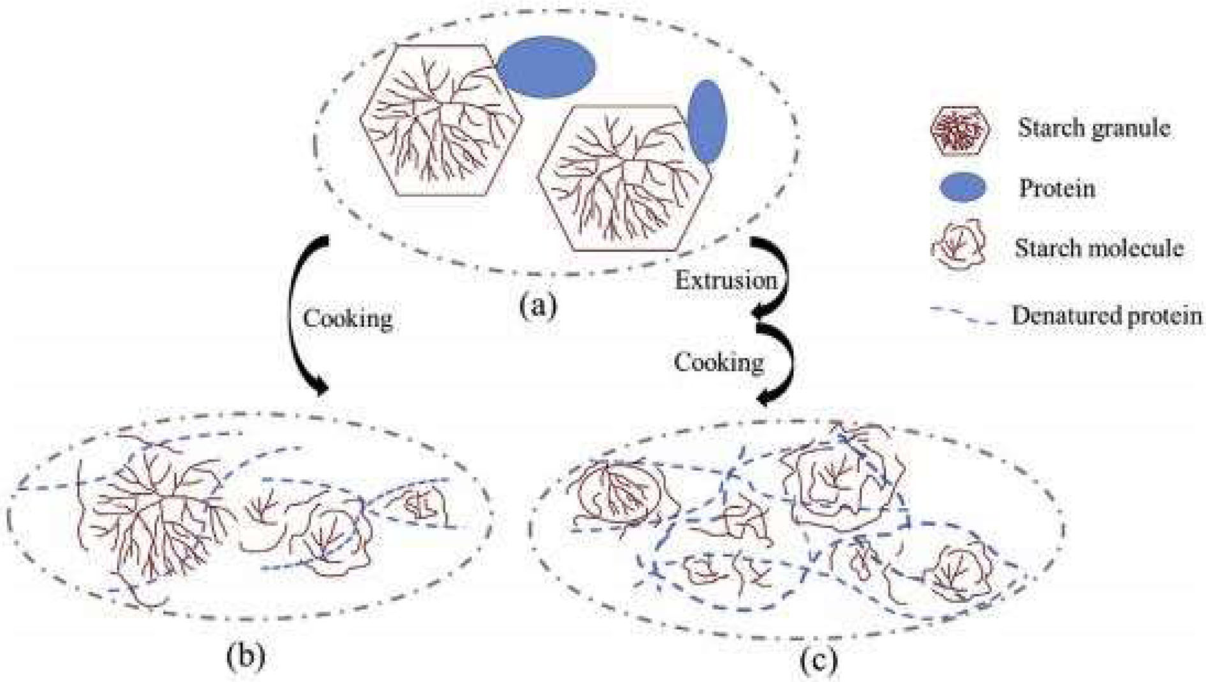

Figure 8. Proposed mechanisms for the reduced starch digestibility of texturized rice. (reproduced from Ye et al. 2019 with permission from Elsevier).

cereals, snacks developed from a variety of cereal-blends, vegetable-based foods, etc. The extrusion process involves mixing, heating, cooking, sharing, and shaping of the final product (Karwe 2009). Rice extrusion results in partial or complete degradation of its crystalline starch structure, amylose-lipid complex formation, protein denaturation, and molecular fragmentation of starch polymers. High amylose rice varieties should be selected during extrusion, as it can reduce cooking losses apart from contributing to the development of amylose-lipid complexes during digestion (Jeong et al. 2016). Even though extrusion processing has a wide product-range, any changes in the feed composition and process variables might affect the product quality and therefore a critical evaluation of process parameters and extrudate characteristics is essential (Gat and Ananthanarayan 2015).

Rice can be extruded either by hot or cold extrusion. Consumption of extruded rice can lower the GI as compared with milled rice or extruded wheat products. This can be attributed to gelatinization and retrogradation of starch that occurs during the process (Panlasigui et al. 1992). During extrusion, high temperature and shear forces destroy the structure of starch and subsequently realign linear amylose molecules in turn resulting in the formation of RS (Castellanos-Gallo et al. 2019). Feng and Lee (2014) reported lower GI values for extruded rice with a significant decrease in RDS levels. During extrusion of rice, additives like fruit peels can further reduce the GI apart from improving the antioxidant activity (Zeng et al. 2019). Ye, Cui, et al. (2019) studied the starch digestibility of texturized rice (TR) using a simulated gastrointestinal tract. The TR showed a lesser extent of starch hydrolysis than the control rice as extrusion increased the RS content. Also, three mechanisms have been proposed to explain the reduction in starch digestibility after the extrusion process: (1) formation of covalent cross-links of protein molecules in the TR that are resistant to protease digestion, (2) protein coating on the starch molecules thus preventing amylase digestion and, (3) formation of a complex structure that is resistant to enzymatic digestion due to the entanglement of protein with starch during extrusion (Figure 8). Recently, Yang et al. (2020) studied the effect of extrusion on the in vitro digestibility of broken rice (a major by-product obtained during rice milling). They observed the rough surface of the extruded rice with a mixture of B and V type crystalline patterns that result in lower starch digestibility. He et al. (2020) also observed reduced starch digestibility of micro-extruded rice starch added with guar gum at various concentrations. During micro extrusion, the structure of starch granules gets destroyed, reforming to a highly stable structure with higher SDS. Upon addition of guar gum during extrusion, RS levels increased with a reduction in the GI. This can be attributed to the fact that guar gum facilitates hydrogen bonding interaction (Figure 9) with the starch structure, forming a single or double helical structure that covers the starch chains and thus protecting against hydrolysis by α-amylase (He et al. 2020).

Effect of other handling and storage methods

Several other post-harvest techniques can have implications on the GI of rice. While most of these are region-specific, very limited information is available on the others.

Aging

Aging or storage of rice is a complex process that starts from the pre-harvesting and lasts until its consumption. There are two types of aging: (1) natural and (2) accelerated; in natural aging, paddy is stored for around 4-6 months

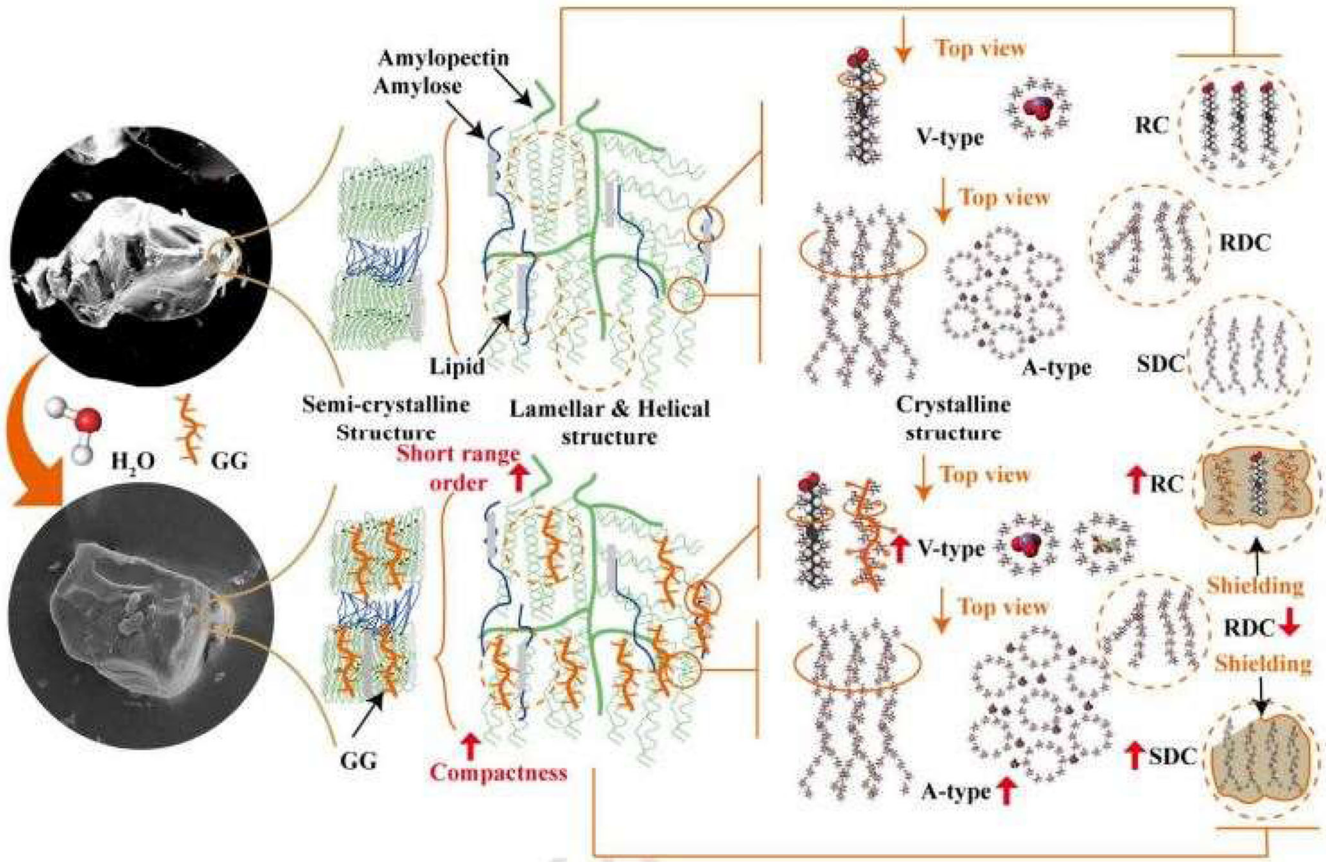

Figure 9. Changes in the starch structure during micro extrusion with guar gum (reproduced from He et al. 2020 with permission from Elsevier).

under normal storage conditions before milling. Since natural aging is a time-consuming process, artificial aging using different techniques has been explored (Saikrishna et al. 2018).In general, the cooking time for aged rice is higher than that for fresh rice; nevertheless, aged rice has its commercial value and consumer preferences. The process of aging results in irreversible changes in the physicochemical properties of rice. Generally, aged rice is priced higher than freshly processed counterparts and is valued for the head rice quality and the characteristic flavor of the cooked product. Also, during processing, aged rice is resistant to swelling (Saikrishna et al. 2018). Sato et al. (2010) reported that the aging of rice noodles under cold conditions could reduce the GI with an increase in RS.

Jaisut et al. (2009) used a high-temperature fluidized bed dryer (130 and 150 °C) for accelerated aging (30- 120 min) of jasmine brown rice in which changes in cooking and sensory properties were reported to be similar to that of naturally aged rice. In the same study, GI of accelerated aged rice was found to be lower than naturally aged rice, owing to the formation of the amylose-lipid complex during the thermal treatment. Moritake (1972) proposed a mechanism for ageing in which lipids in rice get converted into free fatty acids, which form a complex with amylose, thus preventing enzymatic activity on starch molecules. Zhou et al. (2010) reported that the interaction between NSP and starch during the aging process may reduce the GI of rice. Zhou et al. (2016) observed strengthening of the cell wall of white rice during aging (Figure 10) with changes in physicochemical properties and digestive patterns; cooked aged rice was observed to be harder than fresh rice. Also, in the same study, 95% of starch digestion was reported in fresh rice as compared with 79.3%, 83.1%, and 85.2% in aged rice of different varieties. Sittipod and Shi (2016) reported that parboiled rice stored at 25 °C had retrograded starch and amylose lipid complex that may reduce the GI. Millati et al. (2019) performed accelerated aging of IR64 rice at different temperatures (24-30, 40, 50, 60 °C) for 2-4 days in which aging at 40 °C for 4 days was observed to reduce starch digestibility and GI due to starch retrogradation. The interactions between amylose-amylose, amylose-amylopectin, and formation of the amylose-lipid complex during accelerated aging can also inhibit the enzymatic hydrolysis of rice starch, thereby reducing its GI (Millati et al. 2019).

Storage at low temperatures

Storage of rice at low temperatures can modify its starch digestibility by varying the degree of gelatinization and retrogradation. Cooked rice, processed overnight at low temperatures, is recommended for patients with diabetes (unlike freshly cooked rice). It has been reported that storing rice at temperatures between 1-25 °C could increase the rate of retrogradation (Eliasson and Gudmundsson 2006). Thus, retrogradation of rice starch during cooling may increase the RS content, thereby lowering the GI (Englyst, Kingman, and Cummings 1992). During the cooling of cooked rice, the

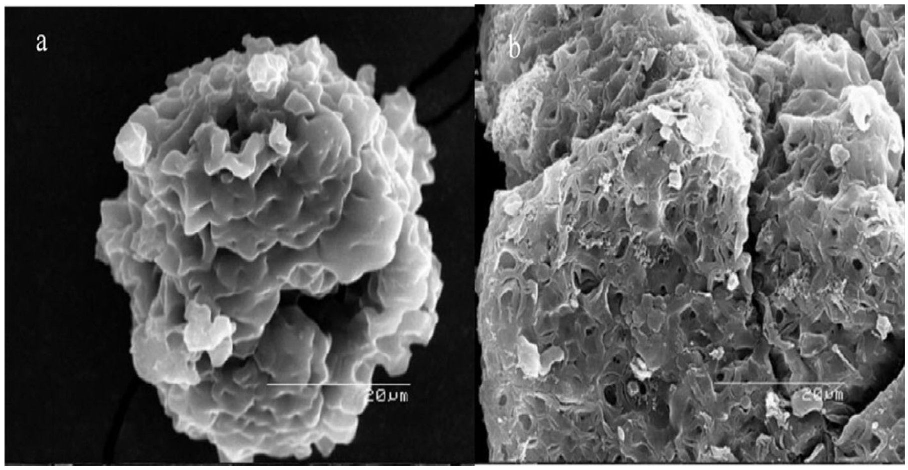

Figure 10. Scanning electron microscopic images of the transverse structure of cooked rice stored at (a) 4 °C and (b) 37 °C for 16 months. (reproduced Zhou et al. 2016 with permission from Elsevier).

amorphous structure of starch gets converted into a crystalline form that can resist enzymatic digestion in the small intestine for up to 3 h (Sajilata, Singhal, and Kulkarni 2006). Goñi, Garcia-Alonso, and Saura-Calixto (1997) reported differences in the GI of freshly cooked and refrigerated cooked rice. In a study by Guraya, James, and Champagne (2001), cooked waxy and non-waxy starches of rice and cooled at 1 °C showed a decrease in starch digestibility by 59% and 42%, respectively. Hu et al. (2004) reported that cooked milled rice stored at 4 °C for 24 h had reduced rates of starch digestibility. In an in vivo study by Sonia, Witjaksono, and Ridwan (2015), the GI of reheated rice after cooling at 4 °C for 24 h was evaluated and the glycemic response of freshly cooked rice was explained with RS content. This was because, when foods with higher starch content are stored at a lower temperature, the amylose and amylopectin molecules tend to form a double-helical structure due to which they lose the water binding ability. Thus, the double helical molecules fail to fit in the binding site of amylase enzyme and their hydrolysis is restricted (Ai, Hasjim, and Jane 2013; Jane and Robyt 1984). Similarly, Lu et al. (2017) observed that consumption of reheated cold-stored parboiled rice can lower the in vivo glycemic responses and its regular consumption may reduce the risk of type II diabetes. However, detailed clinical evidence can supplement these results.

Rewthong et al. (2011) prepared instant rice by conventional boiling and electric cooking methods. The former was frozen at −20°C, cooled at 4°C for 24 h, and then dried to prepare instant rice. The GI of cooled rice (4°C) was found to be higher than the freshly cooked rice and frozen rice (-20°C) as drying during the instant rice production decreased the B type crystalline structure from 1.76% to 0.42%. Thus, freezing of rice could be a beneficial pretreatment in the production of instant rice.

Effect of cooking

Rice is cooked for consumer consumption and during cooking; gelatinization of rice starch occurs that can result in good textural attributes. Also, cooking can improve the bioavailability of diverse nutrients. The conventional method of cooking rice involves boiling in water. Pressure cooking of rice is used as an alternative to the conventional method because of low time and energy requirements, it can also enhance the protein and starch digestibility of rice (Sagum and Arcot 2000). Apart from these common methods, rice can also be cooked in electric cookers or using microwave or stir-frying. Cooked rice can be stored and reheated to modify the retrogradation effects of starch (Boers, Seijen ten Hoorn, and Mela 2015).

Cooking starchy foods can lead to the gelatinization of starch granules, resulting in the loss of amylose and amylopectin crystallinity and thereby producing a disordered structure of starch, making it more susceptible to enzymatic hydrolysis (Jung et al. 2009). Also, cooking rice at a higher temperature may increase the leaching of starch molecules due to gelatinization and thus increasing the GI (Li et al. 2017). Further, the properties of cooked rice depend on cooking time, temperature, and moisture content. Wolever et al. (1986) reported a higher GI for rice boiled for 15 min than those boiled for 5 min and explained the variations to have occurred due to the swelling and splitting effects. Jung et al. (2009) reported lower postprandial blood glucose responses for uncooked rice powder than cooked rice with a higher percentage of gelatinized starch (76.9%). Reed et al. (2013) studied the effect of different cooking methods on the structure of starch and its hydrolysis rate. Stir-fried rice was found to have lower starch hydrolysis characteristics with higher RS content. This was because, stir-frying of freshly steamed rice resulted in the formation of the amylose-lipid complex (Ai, Hasjim, and Jane 2013) apart from lipid coating effects as corn oil was used during frying. Gunathilaka and Ekanayake (2015) observed lower GI for the microwave cooked rice than conventionally cooked rice, but these variations were not distinct.

Ritudomphol and Luangsakul (2019) optimized the cooking temperature and water: rice ratio for instant rice production and cooking at lower temperature and short duration along with higher water ratio could reduce the GI of rice as its structure had fewer voids with the more compact periphery, thus restricting enzymatic digestion. In a recent study, Kim et al. (2020)observed that the retort cooking method produced high RS content in rice (121 °C; 30 min). Even though the conventional cooking method had higher retrogradation enthalpy than the retort cooking method, higher GI was observed. Thus, apart from the resistant starch content (Kim et al. 2020), starch retrogradation is responsible for amylose-lipid complex formation at the cooking temperature that is associated with lower GI values (Derycke et al. 2005). Wang, Chao, et al. (2020) studied the effect of two different cooking methods on the digestibility of starch for pigmented brown rice in which soaking at a higher temperature, followed by shorter heating duration and braising with a rapid reduction in temperature resulted in lesser starch digestibility with increased SDS and RS contents. This was because of an increase in the bulk density of the molecular chain packing in starch, which in turn may reduce the diffusion and penetration of enzymes into starch granules. These results were further confirmed using FTIR (Fourier transform infrared spectroscopy) and SAXS (small-angle x-ray scattering) analyses (Wang, Chao, et al. 2020).

On the contrary, Darandakumbura, Wijesinghe, and Prasantha (2013) explained that parboiling may reduce the GI but cooking methods have no significant effects in altering the GI of rice. This was further reported by Suman and Boora (2015).

Effect of other additives/ingredients

Processed rice is consumed along with one or more added ingredients and hence the cumulative effects on the GI need to be understood. Sharavathy, Urooj, and Puttaraj (2001) studied the effect of accompaniments on the GI of rice-based foods. The findings of the study indicated that added ingredients may manipulate the levels of RDS and SDS by varying the type of accompaniments that were chosen to consume along with the rice. Sugiyama et al. (2003) reported that rice mixed with different forms of soybean had GI lowering effects due to the soluble fiber content and anti-nutrients in soybeans. Chen et al. (2010) observed that stir-fried noodles had low GI (54), whereas, fried noodles with sliced beef had a medium GI (66) as the lipid coating during stir-frying could result in the formation of an amylose-lipid complex.

It was further reported by Putseys, Lamberts, and Delcour (2010)that adding lipids into starch may improve the gelatinization temperature and decrease the swelling capacity and solubility of starch. Besides, the enzymatic digestibility of starch decreases with increased lipid content (Kawai et al. 2012). However, the addition of lipids with waxy starches may have little influence on starch digestibility owing to the reduced capacity to form complexes. Sun et al. (2014) also observed that the addition of chicken (protein), fat, and vegetables to white rice had a lower glycemic response than rice alone. Similarly, Osman, Mohd-Yusof, and Ismail (2017) prepared stir-fried rice with added fat and protein and explained that fat and protein may delay gastric emptying during digestion and in turn affect the GI (Ryan et al. 2013). Giri et al. (2017) studied the effect of added ingredients (barley, oats, gluten, guar gum) on the GI of Indian traditional foods in which oats and guar gum were found to be effective in reducing the GI of rice-based foods. Zhu et al. (2018) reported that the addition of vegetables in the rice meal could decrease the rate of carbohydrate digestion, thereby reducing the GI. Kumar, Sahoo, Sahu et al. (2018) added pigeon pea and ghee in rice and observed an increase in RS content. Also, Kumar et al. (2020) reported that the addition of pigeon pea, ghee, and cauliflower would decrease the GI of rice owing to an increase in the RS content. Ballance et al. (2019) studied the in vivo GI of rice consumed with boiled carrots, poached salmon, and herb sauce. While the GI of the formulation was 28 ± 7.9, cooked rice alone had a GI of 57 ± 17.8. Chusak et al. (2019) studied the impact of cooking methods (microwave, electric cooker) and the addition of *Clitoria ternatea* (CTE) on the starch digestibility of rice. Results of the study showed that rice cooked in the microwave has the lowest GI as the time taken to cook is lower and a lower degree of starch gelatinization makes it hard to digest (Lee et al. 2005). Further, regardless of cooking methods, adding CTE in rice had reduced the starch digestibility. This was because the bioactive compounds (polyphenols, anthocyanins) in CTE inhibit the activity of carbohydrate digestive enzymes, thus reducing GI (Adisakwattana et al. 2012). Further, Camelo-Méndez et al. (2016) reported that amylose could form a complex with polyphenols of CTE which in turn may reduce starch digestibility. Also, the addition of polysaccharides to rice can build a network around the starch granules that is very difficult to get hydrolyzed by digestive enzymes and can therefore decrease GI (Wee and Henry 2020). This is because polysaccharides can interact with starch granules on the surface and act as an enzyme barrier and restrict the leaching of amylose chains during gelatinization (Funami et al. 2005). Apart from that, polysaccharides can form a network around the starch granules, which may restrict its access by the digestive enzymes (Koh et al. 2009). Besides, polysaccharides addition may increase the viscosity of food during digestion which delays glucose release in the small intestine (Marcano, Hernando, and Fiszman 2015). Similarly, Sofi et al. (2020) observed that the addition of germinated flour and protein isolate from chickpea in rice noodles had reduced the RDS significantly with a decrease in the in vitro starch digestibility. Thus, consuming rice with added ingredients that are rich in fiber, protein and fat, could reduce its GI.

Interestingly, the order of consumption can also have implications for GI. Lu et al. (2019) reported that when apple is eaten before rice, the glycemic response reduces without any negative effects on satiety levels. This is attributed to non-sugar components such as insoluble fiber, pectin, and polyphenols which can delay gastric emptying (Dhingra et al. 2012).

Conclusions and directions for research

Rice holds a significant place in the daily diets of millions of people across the world. Given the significance of various food processing technologies on the GI of rice, the task is to deliver rice in the best possible approach to contribute to health. While high GI remains a concern, varietal modifications can alter the GI. From the food technology perspective, the first task is to understand the composition and processing-dependent digestion behaviors and GI of rice. Methods of GI testing require to be optimized, providing results comparable with in vivo trials. Results should explain the implications of both short and long-term consumption of such products. As results could vary with population groups and eating habits, such factors must be taken into consideration. From the technical point of view, another underexplored area is the need to explain the effect of various non-thermal food processing techniques on the GI of rice and rice-based foods. So is the case with several emerging food processing techniques, including 3D printed foods, the effect of plant-based analogues, amongst others. These can provide valuable insights for the future, particularly when one segment of the population is protein and energy-deficient and the other is diabetic.

Disclosure statement

The authors declare no conflicts of interest.

Author contributions

All authors contributed equally for the manuscript to critically review all previous works on the present topic, to draft the manuscript, and to prepare the tables and figures. The review was conceptualized and prepared under the supervision of the corresponding author.

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