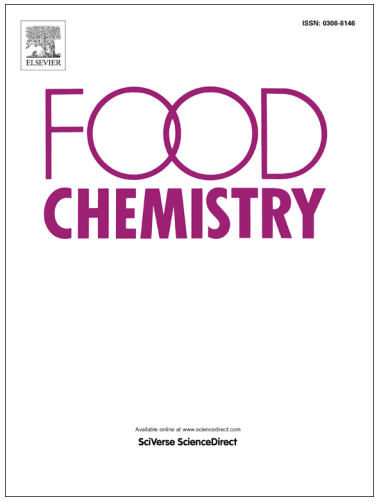

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In vitro gastric digestion of cooked white and brown rice using a dynamic rat stomach model

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Abstract

The changes in physical, rheological and enzyme-digestive behaviours of cooked white and brown rice, with similar amylose content, were investigated using a dynamic *in vitro* rat stomach (DIVRS) model and a static soaking method. The brown rice had a higher resistance on disintegration and lower gastric emptying rate with 53% of the brown rice particles retained in the stomach at the end compared to 32% for the white rice. Furthermore, the release rate of maltose from the starch hydrolysis was higher in the white rice throughout the digestion suggesting the lower glycemic potency of the brown rice. These differences could be contributed from the rigid bran layer in the brown rice which would inhibit the moisture absorption into rice kernels, limit textural degradation, and generate higher gastric digesta viscosity leading to lower mixing and mass transfer efficiency. This study suggests that the structural difference could affect physiochemical properties during gastric digestion.

Keywords: Cooked rice; Gastric digestion; Microstructure; Digesta rheology; Dynamic stomach model

1. Introduction

Rice (*Oryza saliva L*) is one of the most important cereal crops in the world and has been a staple food of over half of the world's population, especially in Asian countries, for centuries (Hu, Zhao, Duan, Linlin, & Wu., 2004). White rice that primarily consists of starchy endosperm is produced through refining processes when the outer bran and germ portions of brown rice are removed. It is accepted that the brown rice consumption is usually associated with lower risk of type 2 diabetes and hyperlipidemia by virtue of its abundances of multiple nutrients (including phytic acid, phenolic compounds, fibres, vitamins and minerals) compared with the white rice (Tian, Nakamura, & Kayahara, 2004). Also, lower blood glucose response to carbohydrate containing in the foods has been suggested to be beneficial in the dietary management of diabetes and hyperlipidemia (Kim et al., 2004; Panlasigui & Thompson, 2006; Sun et al., 2010). However, studies on the effects of the brown and white rice on glucose and insulin levels are contradictory in literature. Some showed that brown rice had a lower rate of starch digestion and postprandial blood glucose response as measured by the glycemic index (GI) than the same amount of the white rice (Foster-Powell, Holt, & Brand-Miller, 2002; Kong, Oztop, Singh, & McCarthy, 2011; Panlasigui & Thompson, 2006) while others reported no difference (Goddard, Young, & Marcus, 1984; Miller, Pang, & Bramall, 1992; Hu et al., 2004). For example, Miller et al. (1992) found that when consumption of the same amount of cooked white and brown rice of the same variety, they had almost the same GI. Nonetheless, another *in vivo* study reported that brown rice was digested slower and resulted in lower GI values and blood glucose response in both healthy and diabetic subjects compared to the white rice prepared from the same rice variety and batch (Panlasigui & Thompson, 2006). The contradictory results are attributed to numerous factors, including the differences in methodology used for investigation, amylose content and physicochemical properties of the rice samples (Foster-Powell et al., 2002;

Hu et al., 2004; Panlasigui & Thompson, 2006; Panlasigui et al., 1991). Compared with other influencing factors, the effect of amylose content on rice GI values and glycemic response has been the most widely studied and generally used as a good predictor of starch digestion rate and blood response (Goddard et al., 1984; Foster-Powell et al., 2002). However, Panlasigui et al. (1991) reported that rice varieties with similar amylose content still differed in starch digestibility and glycemic response in humans, and they concluded that amylose content alone was not a good predictor of starch digestion rate or glycemic response. The physicochemical properties of the rice samples, such as chemical composition, moisture content, rheology, texture and microstructure, could also exert significant influence on rice starch digestion rate (Panlasigui et al., 1991), but few studies have been focused on the changes in these physicochemical properties of the gastric digesta that may further impact intestinal digestion and nutrient release in the gastrointestinal tract.

Research on rice digestion has been conducted using either *in vivo* or *in vitro* approaches. *In vivo* experiments conducted on humans and animals could produce more reliable and accurate results compared with *in vitro* tests, however, they are costly, time-consuming and inconvenient, as well as being impeded by ethical constraints that often limit human or animal experimentation (Bornhorst & Singh, 2014; Yoo & Chen, 2006). The static *in vitro* models, such as shaking bath and magnetic stirrer, have been commonly applied to evaluate *in vitro* digestion, particularly to quantitatively investigate the specific digestion process and mechanism of particle disintegration due to their easy operation and simple structure, although they cannot fully simulate the dynamic mechanical and chemical environment as well as fluid dynamic behaviours encountered *in vivo* (Guerra et al., 2012; Yoo & Chen, 2006). Many dynamic gastric digestion models have also been developed in the past decades, including the TNO gastric model (TIM-1) (Minekus, Marteau, & Havenaar, 1995), dynamic gastric model (DGM) (Wickham, Faulks, & Mills, 2009) and human gastric simulator (HGS) (Kong & Singh, 2010). The main drawback of them is that they all ignored the effect of geometrical morphology and inner physiological

structure of the stomach on digestion and gastric emptying. This might prevent them reproducing the fluid mechanics, distribution of gastric contents, and gastric emptying order encountered *in vivo* (Chen, 2015).

Previously, we reported a dynamic *in vitro* rat stomach (DIVRS) model designed and fabricated based on the principles of morphological bionics (Chen, 2016), that is, the gastric morphology, dimensions and physiological structures, as well as physical movement implemented on the soft silicone rat stomach, are similar to the real rat stomachs (Chen, Wu, & Chen, 2013; Wu, Chen, Wu, X., & Chen, 2014). With the stomach model, the digestive behaviours of the large raw rice particles and casein power suspensions were studied, and the results showed that the dynamic model was effective in showing consistent trends in terms of digestion and gastric emptying behaviours compared with the *in vivo* results obtained from living rats (Chen et al., 2013; Wu et al., 2014). The main objective of this study is to determine the changes in physiochemical properties of the cooked white and brown rice during simulated gastric digestion in the DIVRS model and to elaborate the effect of the physicochemical differences between the two rice varieties on the *in vitro* rice starch digestion rate.

2. Materials and methods

2.1. Materials

2.1.1. Food

White rice and brown rice from the same variety (Golden arowana rice produced in Jilin province of China) were both purchased from a local supermarket. The mean length, width and thickness of the rice particle, as determined by using a Vernier caliper, is about 5.3×2.1×1.6 mm for white rice and 5.0×2.3×1.9 mm for brown rice. The initial moisture contents of the white rice and brown rice as expressed by wet basis (w.b.) were 12.85 ± 0.78% and 13.37 ± 0.65%, respectively. The amylose

contents, as determined by an iodine colorimetric method (Sowbhagya & Bhattacharya, 1971), were 27.55 ± 0.68% for the white rice and 26.18 ± 0.59% for the brown rice (expressed on a basis of total starch).

2.1.2. Preparation of cooked rice

Cooked rice was prepared in an electric rice cooker (QF180D, Galanz, Shunde, China) with a rice: water ratio of 1:1.2 (w/w) for white rice and 1:1.6 (w/w) for brown rice. The white and brown rice were cooked for around 22 and 35 min, respectively. More water and longer cooking time was included for the brown rice in order to achieve rice consistency that was acceptable for consumption. After cooking, the cooked rice was kept warm for 5 min and then cooled down to about 45^{o}C. The initial moisture contents (dry basis) for the cooked white and brown rice were 123.9 ± 7.3% and 101.5 ± 6.3%, respectively.

2.1.3. Chemicals

Artificial rat saliva (7982 U/ml) was prepared by dissolving 532.1 mg porcine pancreatic α-amylase (type VI-B A-3176), 1.17 mg NaCl, 1.49 mg KCl, 21 mg $NaHCO_3$ in 10 ml deionized water adjusted pH of 7.80 using 1 M NaOH (Wu et al., 2014). Artificial gastric juice (252 U/ml) was prepared by dissolving 25.65 mg pepsin (from porcine gastric mucosa, P7000), 15.75 mg $NaHCO_3$, 438.75 mg NaCl in 50 ml deionized water and the pH was adjusted to 1.63 using 1 M HCl (Chen et al., 2013; Kong & Singh, 2010). The pepsin and α-amylase were purchased from Sigma-Aldrich, Inc. (USA). The other chemicals were used as received.

2.2. In vitro digestion of rice in the DIVRS model

2.2.1. Collection of gastric digesta

The DIVRS model, as described previously (Wu et al., 2014), was used to study the gastric digestion of the cooked white and brown rice. As shown in Fig. 1, the model is composed of a soft silicone rat stomach, a compression device, a temperature controlled box and the secreting and emptying system. The cooked brown or white

rice (3 g, dry basis) were mixed with 3 ml deionized water and 1.01 ml simulated saliva (37°C) was added followed by stirring for 2 min with a magnetic stirrer (60 rpm) as a mimic of oral digestion (Wu et al., 2014). A small amount (0.60 ml) of the simulated gastric juice (37°C) was fed to the rat stomach model to mimic the fast state before the food loading (Chen et al., 2013). The compression device was set to create 3 compressions per minute, and the amplitude of the angle plate was set at 2.6 mm, which were determined to produce similar contraction movement occurred *in vivo* (Chen et al., 2013). The gastric juice was fed to the silicone stomach continuously upon the food loading at an average rate of 25 μl/min with the aid of a syringe pump (TJP-3A/w0109-1B, Baoding Longer Precision Pump Inc., China). The gastric digesta was extracted from the pylorus upon digestion at an average rate of 22 μl/min using another syringe pump. The gastric juice secretion and gastric digesta extraction rates were determined in agreement with the *in vivo* data reported previously (Chen et al., 2013). The food samples were digested in the DIVRS model in batches for 0, 10, 20, 30, 40, 60, 90, 120 and 180 min, respectively. For the test of each time point, except 180 min, after the sample was digested for the given time, the DIVRS was stopped and the gastric digesta remaining in the stomach was collected for the measurements of reducing sugar (maltose) and pH. For the remaining gastric digesta obtained from 180 min digestion, apart from the maltose and pH, the gastric retention ratio, particle size distribution and rheology were measured as well.

2.2.2. Determination of gastric digesta pH, maltose concentration and gastric retention (%)

The pH of the gastric digesta with respect to digestion time was determined immediately upon the collection. The maltose concentration was measured by 3, 5-dinitrosalicylic acid colorimetric (DNS) method (Miller, 1959). The gastric retention expressed by dry solid mass retention ratio (%) was calculated as the remaining gastric digesta (dry basis) at the end of digestion divided by the initial dry solid mass of the rice sample introduced into the DIVRS model.

2.2.3. Measurement of particle size distribution

In order to determine the particle size distribution after 180 min digestion, 0.5 g of the gastric digesta was dispersed in glass culture dish (diameter 10 cm) containing 50 ml deionized water to prevent overlap. A digital camera (550D, Canon, Tokyo, Japan) was set in a program mode and fixed at a constant height and position before photos were taken from underneath using a flat light box. Basically, the same kind of lighting and photo-taking conditions for all tested samples were ensured. The images were then masked using Matlab v8.0 (Mathworks Inc., Natick, Massachusetts, USA) to ensure that all the particles were adequately and accurately captured, followed by analyzed using Image J software (Image J, NIH, Maryland, USA) for the measurements of the particle size distribution (as expressed by cumulative percentage of projected area for the rice particulates with different particle sizes), as well as median particle area (x_{50}, mm^2) (Bornhorst et al., 2013b). For comparison, the initial particle size distribution and x_{50} of the white and brown rice samples before being transferred into the DIVRS model was also determined by the image analysis method.

2.2.4. Rheological measurement

The steady shear and dynamic oscillatory tests were conducted with a stress-controlled rheometer (AR-G2, TA Instruments, New Castle, DE, USA) using a 40 mm diameter cross-hatched parallel plate geometry to avoid any wall slip effect. The specific procedures were in line with what had been described by Kong et al. (2011) and Bornhorst et al. (2013c), with some modifications. Care was taken to apply the digesta sample with a volume just enough to fill the gap between the element and geometry (approximately 1 ml), minimizing extrusion of digesta when the upper geometry was lowered to a 4-mm gap point. The strain sweep mode was applied to obtain the linear viscoelastic regime followed by oscillatory measurements over the frequency range of 0.1-100 rad/s. The steady shear measurements were performed for shear rates ranging from 0.1 to 100 1/s. All measurements were performed at 37^{o}C and were carried out in triplicate.

2.3. Static soaking trials

Static soaking method was used to study the moisture absorption, texture and microstructure of rice samples during gastric digestion. The specific procedures were described in Supplementary Material.

2.4. Statistical analysis

All trials were carried out in triplicate and the results were expressed as means ± standard deviations. Significance tests were conducted using analysis of variance (ANOVA) in the GLM procedure of the SAS system to compare the physicochemical differences between the cooked white and brown rice during simulated gastric digestion. Statistical significance (p-value) was set at a probability level of 0.05.

3. Results and discussion

3.1. pH of gastric digesta during rice digestion in the DIVRS model

Fig. 2 shows the pH of gastric digesta of the white and brown rice after gastric digestion in the DIVRS model for different periods of time. Statistical analysis indicates no significant difference in the pH of the two rice varieties throughout the digestion process ($p>0.05$). It can be seen that the pH of both white and brown rice increased dramatically to almost neutral upon the food feeding due to the diluting effect of the rice sample and the consumption of the acid by hydrolysis, followed by gradual decrease because of the continuous secretion of the simulated gastric juice. The variation trend of the gastric digesta pH with respect to digestion time was in line with the results reported by Kong et al. (2011).

3.2. Particle size distribution before and after digestion in the DIVRS model

Fig. 3A shows an example of the images of the white and brown rice dispersed in deionized water before and after 180 min digestion in the DIVRS model. Direct observation revealed that the rice particles before being introduced into the model

were similar, however, more fragmentation was observed for the white rice compared to the brown rice after mechanical and enzymatic treatment in the DIVRS model for 180 min, suggesting the fragility of the white rice at given conditions. The initial and final particle size distributions of the white and brown rice as expressed by cumulative percentage of projected area are shown in Fig. 3B. At the initial time point (t=0), the median particle area (x_{50}, mm^2) between the white rice (6.58 ± 3.25 mm^2) and brown rice (6.84 ± 2.98 mm^2) was statistically indifferent ($p>0.05$). After 180 min digestion in the DIVRS model, both the white rice and brown were significantly reduced into smaller pieces due to the combined actions of physical force, as well as enzyme digestion and acidic hydrolysis, which are parallel to the report of Kim et al. (2004). However, the degree of fragmentation for the brown rice was significantly lower than that for the white rice ($p<0.05$), with x_{50} of 1.19 ± 0.78 mm^2 and 3.38 ± 1.16 mm^2 in the end for the white and brown rice, respectively. Further, the percentage of small size rice particles (less than 10 mm^2) in the brown rice digesta (62%) was significantly lower compared to that in the white rice (88%), suggesting that more brown rice with large-size particles remained in the DIVRS model than the white rice at the end of digestion ($p<0.05$). The finding was consistent with the *in vitro* results, previously reported by Kong et al. (2011), that 80% of the white rice particles were smaller than 10 mm^2 compared to 40% for the brown rice after 180 min digestion in a human gastric simulator (HGS). In addition, a close observation reveals that the large pieces of the brown rice were generally attached with bran layer (Fig. 3A), confirming the protective effect to resist breakdown thus going against nutrient release from the brown rice (Panlasigui et al., 1991; Panlasigui & Thompson, 2006).

3.3. Rheology of the gastric digesta

A good understanding of rheological properties of gastric digesta is important to evaluate and control food design and processing, as well as to establish relationships between structure and flow, mixing, digestion and absorption in the GI tract (Lentle & Janssen, 2008). Fig. 4A shows storage modulus (G') and loss modulus (G'') of the gastric digesta of white and brown rice after 180 min digestion in the DIVRS model.

Both of the digesta was particle-dominated system, generally showing weak gels or more solid-like behaviour (Löfgren, Walkenström, & Hermansson, 2002), with G' always greater than G'' and almost constant with frequency over the whole frequency range studied under small deformation oscillatory measurements. The dynamic (complex) and steady shear (apparent) viscosity of the gastric digesta is shown in Fig. 4B. It can be seen that the complex or apparent viscosity decreased with the increase in frequency or shear rate, indicating shear-thinning behaviour of the gastric digesta (Löfgren et al., 2002) under large deformation measurements. Furthermore, the complex viscosity was always significantly larger than the apparent viscosity within the frequency and shear rate range studied (Fig. 4B), indicating structural breakdown of rice particles or weak gel networks under large deformation conditions (Takahashi & Sakata, 2002). The brown rice displayed significantly higher viscosity than the white rice in the range of tested frequency or shear rate, which was believed to result from the high concentration of dietary fibre present in the bran layer of the brown rice that would increase the viscosity (Panlasigui et al., 1991; Kong et al., 2011; Bornhorst et al., 2013c). Additionally, more particles with larger size in the brown rice digesta (Fig. 3B) could also contribute to the higher viscosity due to its particle-dominated property (Takahashi & Sakata, 2002). These indicate that the difference in structure between the rice varieties could affect the rheological behaviour of the rice samples during simulated gastric digestion. Analogy to *in vivo* system, the increased digesta viscosity could lead to lower mixing and digestive efficiency, decreased activity of enzymes as well as reduced mass transfer across the intestinal wall, resulting in lower amounts of nutrient absorption in the gastrointestinal tract (Bornhorst et al., 2013a).

3.4. Maltose concentration of the gastric digesta during digestion in DIVRS model

The change in maltose concentration of the gastric digesta of the white and brown rice during digestion in the DIVRS model is presented in Fig. 5. The trend between the white and brown rice is similar, with rapid increase in the first 60 min followed by approaching to equilibrium in the end. The initial rapid increase of rice starch hydrolysis was due to the enzymatic action of α-amylase on the readily

available glucans in excess substrate conditions. With the continuous gastric emptying and the secretion of gastric juice, the pH of the stomach decreased along with excursion of the α-amylase out of the stomach. Thus, the limited amount of substrate (rice) available for digestion along with the decrease in pH (Fig. 2) resulted in the reduction of activity of α-amylase as well as the rate and extent of starch hydrolysis.

When compared between the rice varieties, however, the extent of digestion between the white and brown rice is largely different. As shown in Fig. 5, the white rice produced consistently higher maltose concentration with a final concentration of 73 mg/ml, which is significantly higher than that of the brown rice (52 mg/ml, $p<0.05$), indicating a greater level of solids dissolution and starch hydrolysis occurred in the white rice. The result is in accordance with previous studies, confirming the lower starch digestion rate and gastric glycaemic potency of the brown rice (Foster-Powell et al., 2002; Kong et al., 2011; Panlasigui & Thompson, 2006; Sun et al., 2010). For example, Panlasigui & Thompson (2006) reported that the total sugar released from the brown rice *in vitro* was 23.7% lower than in white rice. Considering the steady flow of digesta, the lower digestion rate of the brown rice also contributes to the proportionately lowering of gastric emptying rate. At the end of digestion, 32% of the white rice retained in the soft stomach model, as compared with 53% for the brown rice (shown in Figure S1 of Supplementary Material), indicating lower gastric emptying rate of the brown rice. The different starch hydrolysis and gastric emptying rates are possibly associated with the differences in chemical composition and physicochemical properties between the white and brown rice (Panlasigui & Thompson, 2006). As shown from the static soaking results, the white rice absorbed more gastric juice (see Figure S2 of Supplementary Material) and had lower hardness (see Figure S3 of Supplementary Material) compared to the brown rice throughout the gastric soaking. This is mainly due to the presence of the bran layer in the brown rice that hindered the absorption of gastric juice into the rice endosperms, thus limiting the textural degradation (McIntyre, Vincent, Perkins, & Spiller, 1997; Sun et al., 2010). Similar results have also been reported by Kong et al. (2011) that the bran layer that

envelops the rice kernels could act as a physical barrier for entry of water and impede the swelling of the starch granules during heat treatment and gastric digestion. Furthermore, the dietary fibre-rich bran fraction is likely to continue to serve as a barrier to digestive enzyme action (McIntyre et al., 1997). A previous study has shown a negative relationship between phytic acid intake and blood glucose response (Yoon, Thompson, & Jenkins, 1983). Thus the phytic acid and polyphenols, which are more concentrated in the bran layer of the brown rice, could also have contributed to the slower starch digestion rate and lower blood glucose response. In addition, the higher viscosity of gastric digesta of the brown rice (Fig. 4) that would lead to insufficient flow and mixing could be another factor leading to lower starch digestion and gastric emptying rates (Lentle & Janssen, 2008). It is known that the slower rate of gastric emptying suggests decreased feeling of hunger and reduced food ingestion that is beneficial to health when eating the brown rice (McIntyre et al., 1997).

3.5. Microstructure of the rice samples after static soaking

Paraffin tissue sections of rice samples were obtained to explore how the structural difference between the white and brown rice influences the digestion rate and the microstructural changes during simulated digestion. Figure 6A and B show the morphology and microstructure of the cooked white and brown rice after static soaking for 60 min, respectively. The microstructural properties of the rice samples prior to soaking (t=0 min) and after 180 min soaking in the simulated gastric juice were presented in Figure S4 of Supplementary Material. Morphologically, the white rice and brown rice were similar with oval shape, except the white rice was a little longer in length compared to the brown rice (Fig. 6A-a1 and Fig. 6B-b1). As shown in the histological images, the periphery of the white and brown rice both remained relatively intact after gastric soaking, whereas the central areas contained a few cracks or voids. This could be the natural phenomena occurring during cooking or an artefact on sample preparation. As reported by Ogawa, Glenn, Orts, & Wood. (2003), the voids account for most of the deformation and swelling of grain during cooking and digestion, and they are probably the result of rapid pressure build up (steaming) and

subsequent expansion due to gastric juice absorption or localized exploration. The cracks and voids may be served as channels for gastric juice diffusion thus facilitating enzymatic digestion and acidic hydrolysis during digestion. Compared with the white rice (Fig. 6A), the structure of the brown rice kept relatively intact with fewer and smaller cracks or voids in the central areas and more compact cell arrangements (Fig. 6B). Furthermore, a large number of white rice cells were broken down or dissolved due to the role of enzymatic action, whereas fewer cells were degraded in the brown rice particularly at the peripheral area. As shown for the brown rice, a coated layer was observed at the peripheral area (arrows in Fig. 6B) which is considered as a bran layer (Tamura & Ogawa, 2012). The presence of intact bran layer could prevent the diffusion of both gastric juice and digestive enzymes leading to reduced starch hydrolysis rate. With the continuous absorption of gastric juice, the reduction of cohesive force between the bran cover and endosperm cells of the brown rice led to the separation and exfoliation of bran cover from the endosperm of brown rice (Fig. 6B and Fig S4B of Supplementary Material). A close observation (Fig. 6B-b2) reveals that the digestion of the brown rice was confined mainly along the central areas to the periphery due to presence of the bran layer, which could impede the further diffusion of gastric juice into the inside of brown rice and other regions (Tamura et al., 2014). However, due to lack of the bran layer in the white rice, the gastric juice could diffuse into the inner layers through various paths (Fig. 6B-a2). As a result, both the peripheral and central areas experienced significant digestion in the white rice thus leading to a higher amount of nutrient release compared to that in the brown rice (Fig. 5).

4. Conclusion

We studied the changes in physicochemical properties of the cooked white and brown rice with similar amylose content during simulated gastric digestion in the DIVRS model as well as the moisture absorption, textural and

microstructural changes using a static soaking method. In contrast to the white rice, the rigid bran layer in the brown rice serving as a physical barrier could inhibit the diffusion of both gastric acid (for hydration) and enzymes (for hydrolysis) into the rice kernels during simulated gastric digestion, limiting textural degradation and generating a higher gastric digesta viscosity, and finally leading to the lower starch digestion and gastric emptying rates. The results indicate that the bran layer could be one of the most important factors affecting the physicochemical properties (such as moisture absorption, rheology, texture and microstructure) of the cooked white and brown rice that could further impact the nutrient release rate during simulated gastric digestion.

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Figure captions

Fig. 1. The dynamic *in vitro* rat stomach (DIVRS) system. (1) soft *in vitro* rat stomach model; (2) compression device; (3) one-way valve; (4) model oesophagus; (5) model duodenum; (6) compression plate; (7) fixed support; (8) tubes for gastric juice secretion; (9) sensor of the thermostat; (10) lamps; (11) temperature controlled box; (12) syringe pump; (13) syringe.

Fig. 2. Gastric digesta pH of the cooked white and brown rice during gastric digestion in the DIVRS model.

Fig. 3. An example of the images of the white and brown rice dispersed in distilled water before (t=0 min) and after (t=180 min) gastric digestion in the DIVRS model (A). Comparison of particle size distribution as expressed by cumulative percentage of projected area (B).

Fig. 4. Rheology of the white and brown rice after gastric digestion in the DIVRS model for 180 min. A-storage modulus (G') and loss modulus (G''); B-dynamic or steady shear viscosity (The symbols of solid and unfilled square/triangle represent dynamic and steady shear viscosity, respectively).

Fig. 5. Maltose concentration of the gastric digesta of cooked white and brown rice during gastric digestion in the DIVRS model.

Fig. 6. Morphological (a1, b1) and microstructural properties of cooked white (A) and brown (B) rice after static soaking for 60 min. Images of a3, a4 and b3, b4 are magnifications of particular sections (rectangle area) of a2 for white rice and b2 for brown rice, respectively. Red arrows indicate the bran layer of the cooked brown rice. Scale bars of a1/b1, a2/b2 and a3/a4/b3/b4 are 1 mm, 200 μm, 100 μm, respectively.

Figures

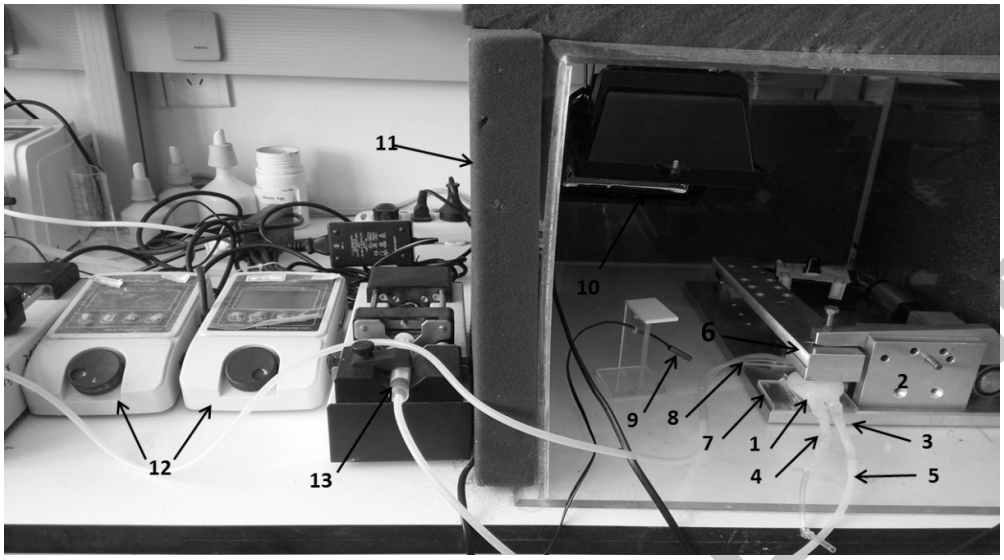

Figure 1

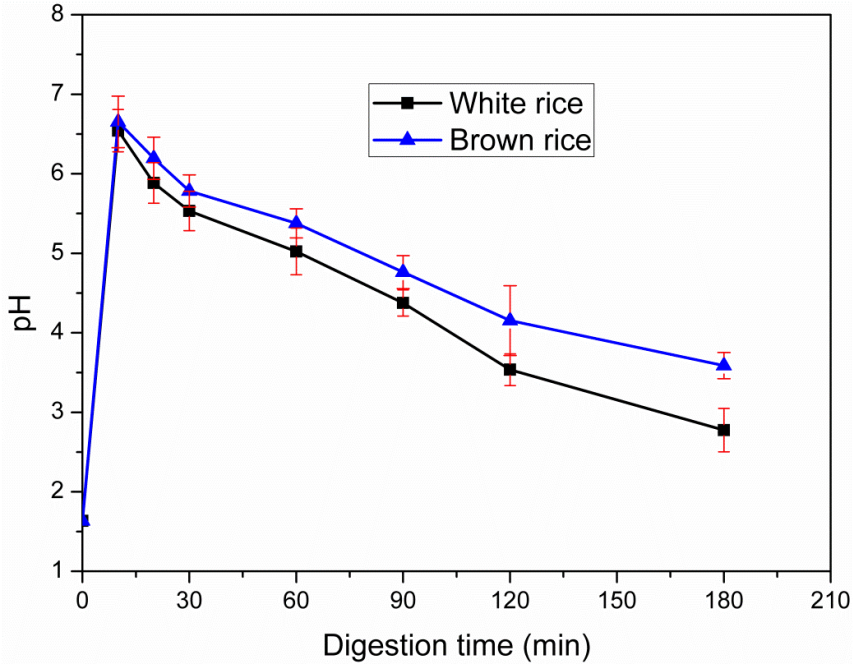

Figure 2

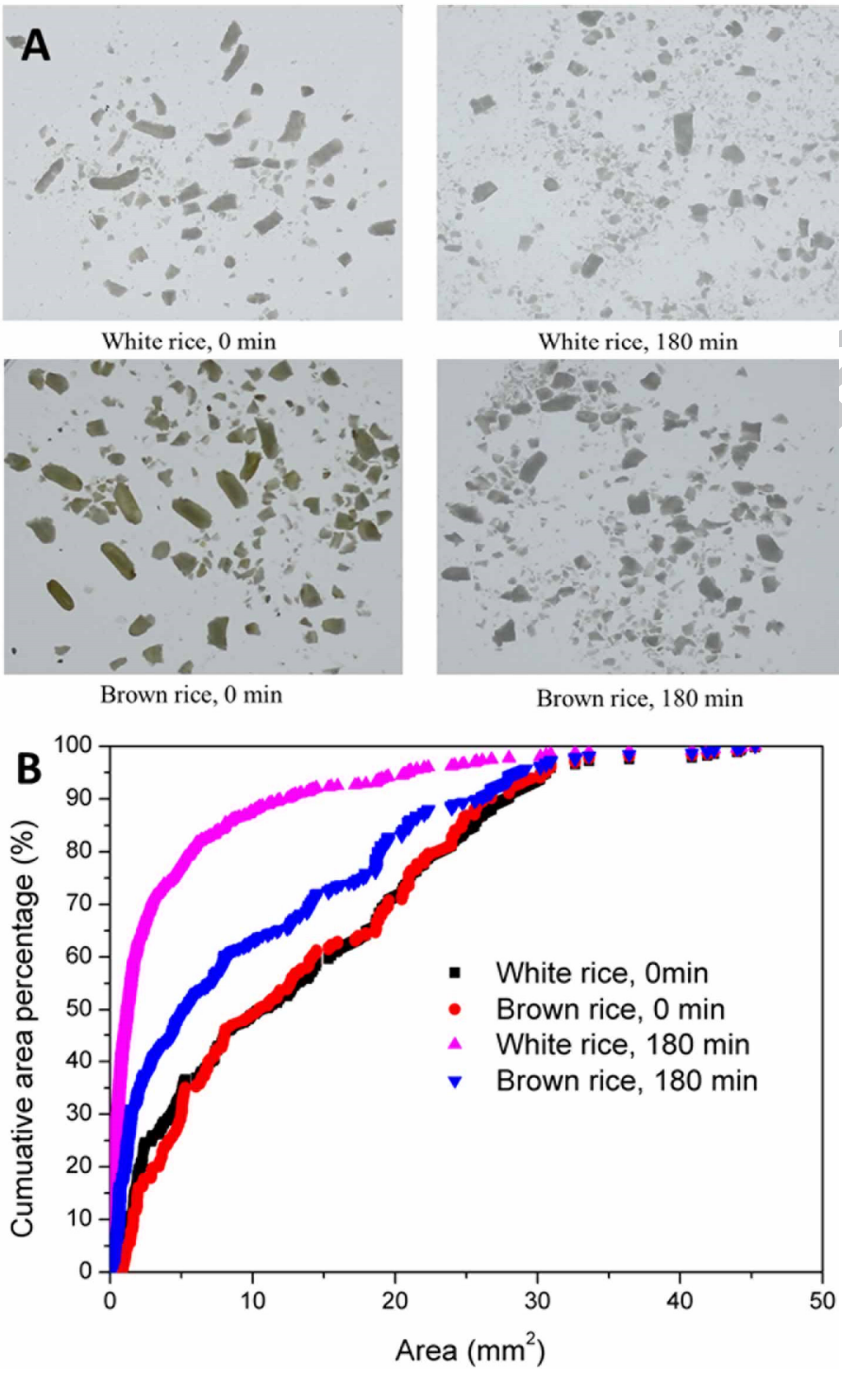

Figure 3

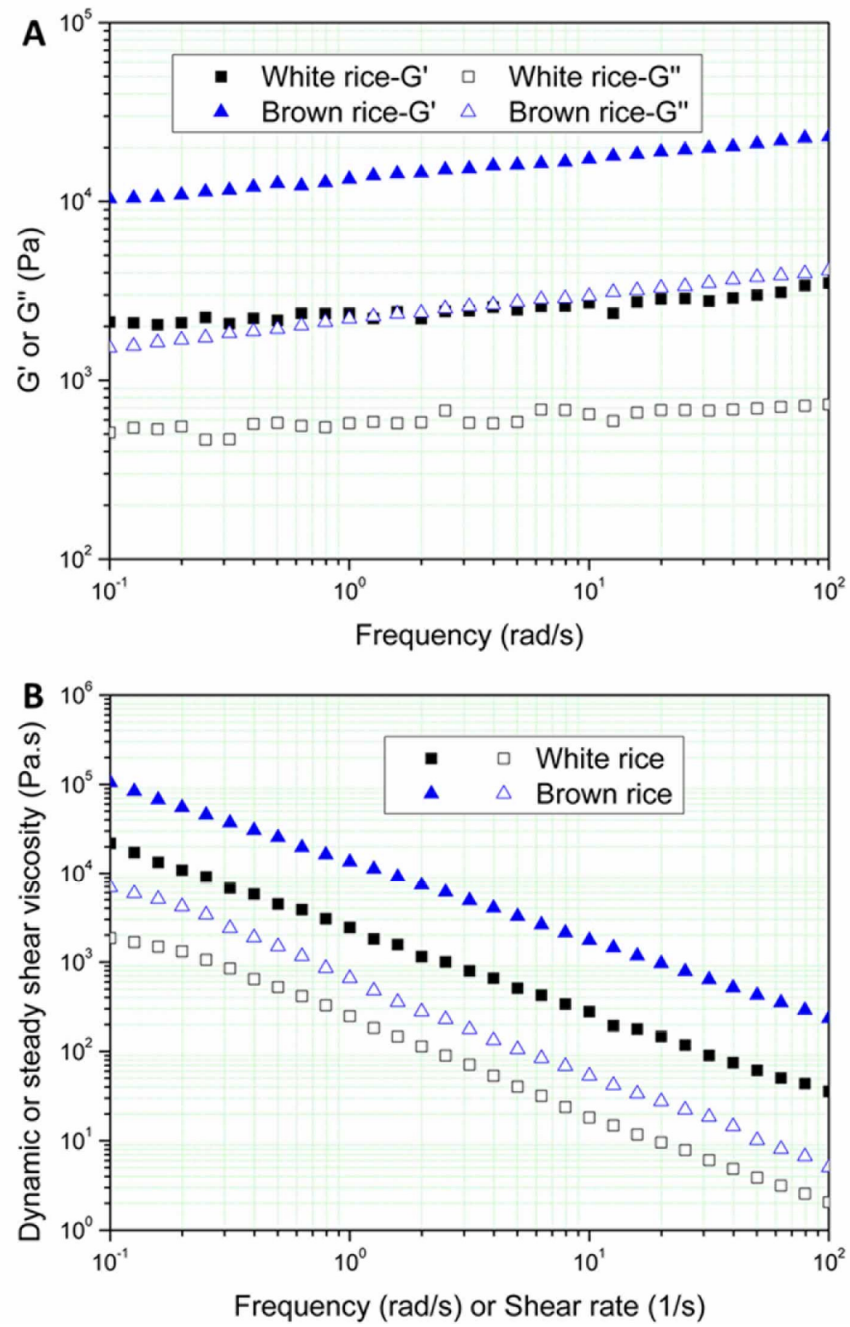

Figure 4

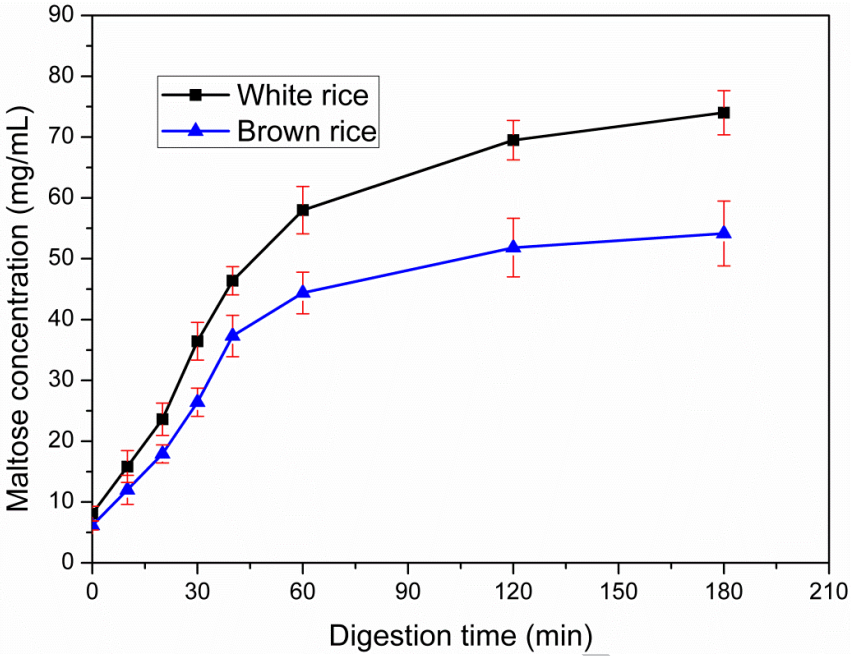

Figure 5

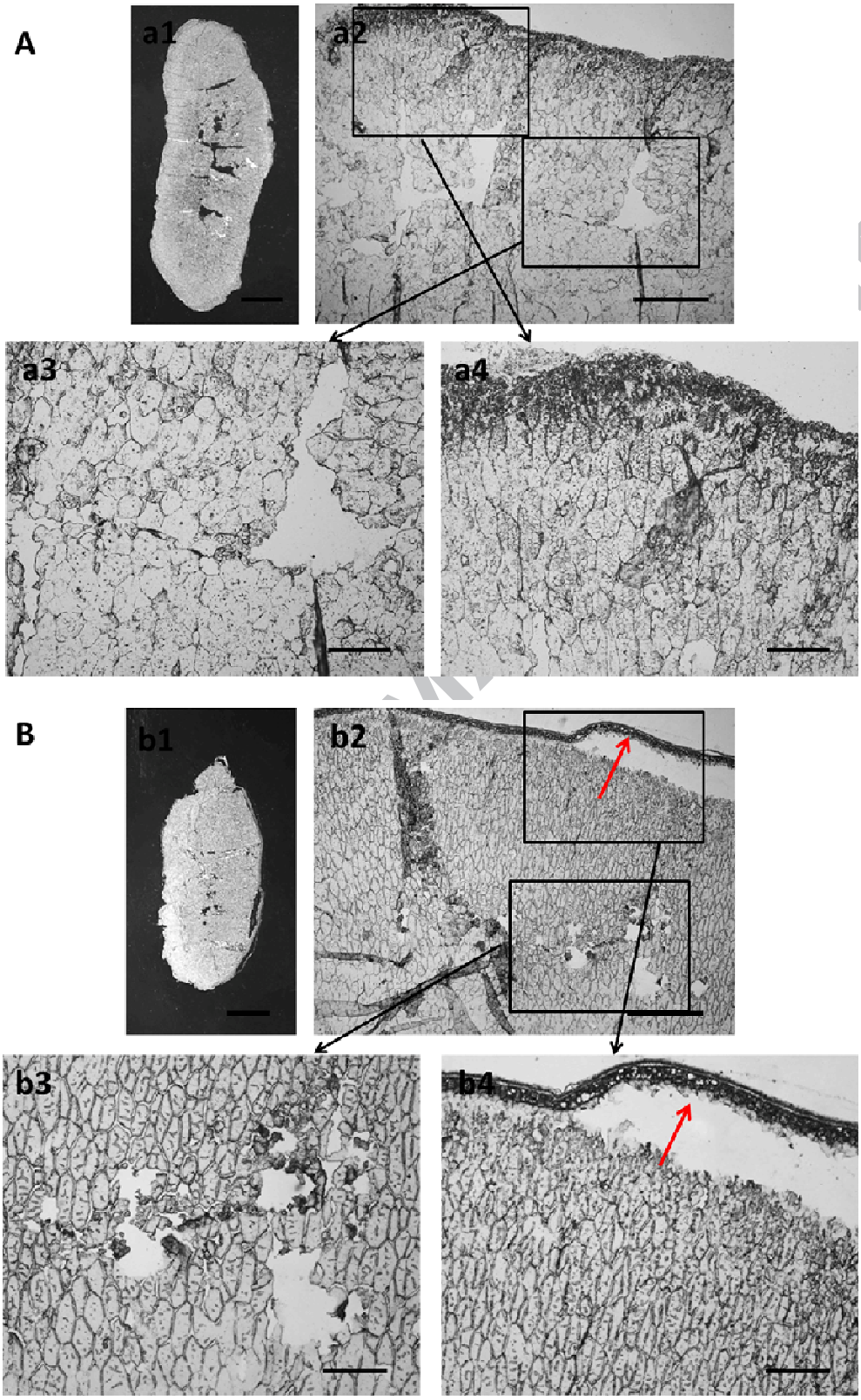

Figure 6

Highlights

- **Digestion of cooked white and brown rice using a rat stomach model**
- **Physicochemical changes during simulated gastric digestion**
- **Brown rice had lower rates of starch hydrolysis and gastric emptying**
- **Bran layer inhibited gastric juice absorption and textural degradation**