# Effects of Cultivar and Processing Condition on Physicochemical Properties and Starch Fractions in Parboiled Rice

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**ABSTRACT**

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Starch can be classified into rapidly digestible starch (RDS), slowly digestible starch (SDS), and resistant starch (RS) according to its resistance to amylolytic enzymes. This study investigated the effects of cultivar and feedstock under varying parboiling conditions on the physicochemical properties and starch fractions of parboiled rice. Rice (rough or brown) was soaked, steamed under pressure, dried immediately or stored at room temperature for 24 hr prior to drying, and then treated with or without a repeated steam cycle prior to milling. The storage treatment significantly increased the retrograded amylopectin enthalpy and amylose-lipid complex melting temperature of parboiled rice. Parboiled rice samples prepared from brown rice feedstock had higher peak melting temperatures but lower enthalpy values of retrograded amylopectin than samples prepared from rough rice after the storage treatment. The pasting viscosity of parboiled rice was most affected by the repeated autoclaving treatment and cultivar. Starch fractions in parboiled rice were significantly affected by cultivar and storage and by the interactions of cultivar and parboiling conditions. The storage treatment significantly increased SDS and generally decreased RDS in parboiled rice. Parboiled rice with different SDS and RS contents can be produced by varying rice cultivar and parboiling conditions.

There is a growing awareness among consumers of the importance of the glycemic index (GI) of foods because health problems associated with obesity are becoming a major health concern in industrialized countries. GI is a measure of the impact of carbohydrates on blood sugar level (Jenkins et al 1981) and is calculated using the area under the blood glucose response curve after the consumption of carbohydrates from a test food relative to a control food of either glucose or white bread. Foods with a GI of 55 or lower, 56–69, and 70 and above are classified as low, medium, and high GI, respectively (FAO/WHO 1998). Research has shown that consumption of low-GI food can be used in the prevention and management of type II diabetes (Fontvieille et al 1988; Jarvi et al 1999).

Many factors affect the digestion and absorption of carbohydrates, such as food composition, botanical source of starch, and starch chemical composition and structure. Behall et al (1998) reported that the ratio of amylose to amylopectin in starch has an impact on the glycemic response to starch-based foods. Engylst et al (1992) classified starch into three fractions according to its resistance to amylolytic enzymes: rapidly digestible starch (RDS), which is hydrolyzed within 20 min; slowly digestible starch (SDS), which is hydrolyzed between 20 and 120 min; and resistant starch (RS), which is not hydrolyzed within 120 min. RDS releases glucose quickly into the bloodstream, causing a higher blood glucose response. SDS causes a slow increase of blood glucose levels and is considered to have a low-to-medium GI (Englyst et al 2003; Lehmann and Robin 2007). RS, considered a dietary fiber, has many positive effects on digestive health when fermented in the gut, such as the production of beneficial short-chain fatty acids that have been shown to improve colon health (Bird et al 2000). High-fiber foods have been shown to produce low glucose responses in normal and diabetic people (Potter et al 1981; Salmeron et al 1997).

Rice is one of the most important crops in the world and provides a major source of carbohydrates for many countries. The GI of cooked rice has been reported to range from 54 to 121 when a reference of 100 is used (Jenkins et al 1981, 1988; Brand et al 1985). Parboiling is a hydrothermal treatment to improve the milling, nutritional, and organoleptic properties of rice (Raghavendra Rao and Juliano 1970; Luh and Mickus 1980; Bhattacharya 1985). Traditionally, the parboiling process consists of soaking rough rice at room temperature, steaming or boiling at 100°C, and then sun drying (Bhattacharya 1985; Kar et al 1999). It has been reported that parboiled rice has a relatively low GI of 54 and 65 by Jenkins et al (1988) and Granfeldt et al (1992), respectively, and that it has higher RS than nonparboiled rice (Eggum et al 1993; Marsono and Topping 1993; Tetens et al 1997). Rashmi and Urooj (2003) reported that rice steamed for 20–40 min had decreased RDS levels but increased SDS levels. Storage of cooked rice has also been shown to increase SDS content. Niba (2003) reported that autoclaved rice stored at ambient temperature for 10 days had higher SDS content than that stored at freezing temperature (–20°C). Storage allows starch to retrograde, which renders starch more resistant to enzymatic degradation (Eerlingen et al 1994; Fredriksson et al 2000; Frei et al 2003).

Traditionally, rough rice is used as the feedstock for parboiling rice. More recently, brown rice is also used for parboiled rice production because of faster hydration (Luh and Mickus 1980; Kar et al 1999). It has been reported that the parboiling conditions can be altered to promote the formation of ordered starch structures such as crystalline amylose and amylopectin and amylose-lipid (AML) complex, thus decreasing starch digestibility and GI (Hoover and Vasanthan 1993; Hoover and Manuel 1996; Chung et al 2009). The objectives of this study were to investigate how cultivar and feedstock under different parboiling, storage, and milling conditions affected the physicochemical properties and starch fractions (RDS, SDS, and RS) in the resultant parboiled rice.

## MATERIALS AND METHODS

### Materials

Two long-grain cultivars, Wells and XL723, that were grown in Arkansas in 2008 were provided by the University of Arkansas Rice Processing Program. Wells is the most widely grown long-grain rice in Arkansas, whereas hybrid rice cultivars such as XL723 are increasing in acreage. Rough rice samples were dried to approximately 10–12% moisture content (MC) at ambient temperature and stored in sealed plastic containers at ambient temperature for six months prior to further treatment. The apparent

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amylose content of rice flour from each cultivar was determined by iodine colorimetry as described by Juliano et al (1981).

Amyloglucosidase from *Aspergillus niger* (300 U/mL) and porcine pancreatin (pancreas activity 200 U), glucose, and 4-morpholinepropanesulfonic acid sodium were purchased from Sigma-Aldrich (St. Louis, MO). Sodium acetate trihydrate was purchased from J. T. Baker (Phillipsburg, NJ), benzoic acid and dimethylsulphoxide from EMD (Gibbstown, NJ), and calcium chloride dihydrate from EM Science (Darmstadt, Germany). A total starch kit containing thermostable α-amylase amyloglucosidase and glucose-oxidase peroxidase was purchased from Megazyme (Wicklow, Ireland).

**Water Absorption**

The water absorption curves of rough and brown rice from each cultivar during soaking were determined to establish the optimum soaking duration of the parboiling process for each feedstock. About 20 g of rough or brown rice kernels was weighed and placed in a beaker containing 40 mL of deionized water at 65°C, which was ~5°C below the onset gelatinization temperature of both rice cultivars as determined with differential scanning calorimetry (DSC) (Diamond DSC, Perkin-Elmer, Norwalk, CT). The beaker was placed in a water bath at 65°C, and rice samples were removed periodically from the beaker, pat dried, and weighed. The MC of the soaked rice was calculated based on the initial dry weight by using the equation below, and it was plotted against soaking time to obtain the water absorption curve.

$$\text{MC}(\%) = 100 \times \frac{\text{final wet weight} - \text{initial dry weight}}{\text{initial dry weight}}$$

**Parboiling**

Two hundred grams of rough rice and brown rice from each cultivar was soaked in 600 mL of deionized water in a water bath (OLS200, Grant Instruments, Cambridge, UK) at 65°C for the time periods that were determined from the water absorption curves. Soaked samples were removed from the soaking water and then autoclaved (Tuttnauer Brinkman 2340E, Westbury, NY) at 120°C and 17–18 psi for 20 or 40 min. After autoclaving, samples were treated under three different storage conditions prior to drying: cycle 1 was without storage; cycle 2 was placed at room temperature for 24 hr; and cycle 3 was placed at room temperature for 24 hr, reautoclaved at its original conditions, and placed at room temperature for 24 hr. After the storage treatment, samples were dried in an oven at 50°C for 3 hr to reach a final MC of 10–12%.

Two hundred grams of each treated rough rice sample were dehulled using a dehusker (THU-35, Satake, Hiroshima, Japan). Half of the recovered brown rice was used directly, and the remaining half was milled in a friction mill (McGill Miller #2, Papsoco, Brookshire, TX) for 30 sec. The brown and milled rice were separated into head rice and broken kernels using a double-tray sizing machine (GrainMan Machinery, Miami, FL). The head rice obtained was ground into flour with a cyclone sample mill (UDY, Ft. Collins, CO) fitted with a 0.25-mm mesh sieve.

**Thermal Properties**

Thermal properties were assessed with DSC. Approximately 10 mg of rice flour was weighed into a stainless steel DSC pan, and 20 μL of deionized water was added by a microsyringe. The mixture was hermetically sealed and equilibrated at room temperature for at least 24 hr prior to heating from 25 to 180°C at 10°C/min. An empty pan was used as the reference.

**Wide Angle X-Ray Powder Diffraction**

The X-ray powder diffraction pattern of rice flour samples was obtained using an analytical diffractometer (Philips, Almelo, Netherlands) with a copper anode X-ray tube. The diffractometer was operated at 27 mA and 50 kV and with a reflection angle (2Θ) from 5° to 35° at a 0.1° step size with a count time of 2 sec. A 100% relative humidity chamber was used to equilibrate samples for 24 hr prior to scanning.

**Pasting Properties**

The pasting properties of rice flour were determined using a Rapid Visco Analyser (Newport Scientific, Warriewood, Australia) operated at 160 rpm according to AACC International Approved Method 61-02.01 (2010) with modification. Rice slurry was prepared by mixing 3.0 g of rice flour (12% moisture basis) with 25.0 mL of deionized water in a canister (10% w/w). The slurry was heated from 50 to 95°C at 3°C/min, held at 95°C for 10 min, cooled to 50°C at 3°C/min, and held at 50°C for 10 min.

**Starch Digestibility**

Starch fractions, including RDS, SDS, and RS, of rice flour samples were determined by following the method of Englyst et al (1992) with the modifications that invertase and glass marbles were not used in the procedure and that RDS, SDS, and RS were calculated based on a dry starch basis.

**Data Analysis**

A completely randomized 2 × 2 × 2 × 2 × 3 factorial design with two cultivars, two feedstocks, two autoclaving durations, two final products, and three storage treatments was utilized to evaluate these factors on starch digestibility. The experiment was performed in duplicate, and each property was measured at least in duplicate. The data were statistically analyzed, with correlations and multiple linear regression produced with the JMP program (version 8, SAS Institute, Cary, NC) to evaluate the effects of the five factors and their interactions.

## RESULTS AND DISCUSSION

**Water Absorption**

The apparent amylose contents of Wells and XL723 were 26.0 and 22.0% (db), respectively. The water absorption curves of rough and brown Wells and XL723 rice cultivars at 65°C are shown in Figure 1. The initial MC was 14.9 and 13.9%

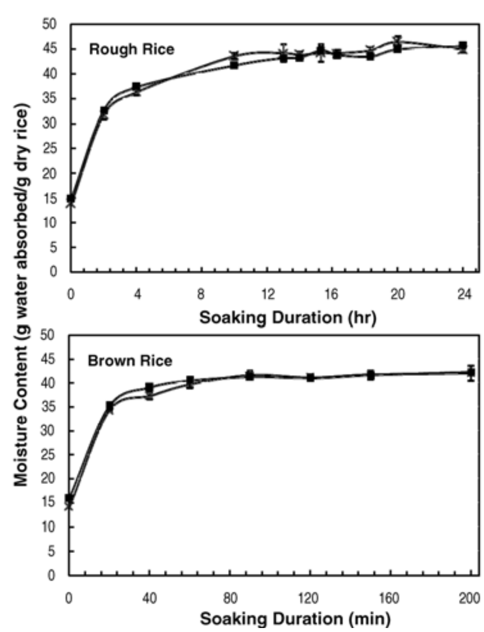


**Fig. 1.** Moisture gain by rough rice and brown rice of Wells (■) and XL723(×) rice cultivars at 65°C.

for rough rice and 16.0 and 14.2% for brown rice of Wells and XL723, respectively. Both cultivars showed similar absorption characteristics for rough rice and brown rice, with a rapid increase in MC in the beginning and then gradually reaching a plateau. The equilibrium MC was approximately 45.5% after 15 hr for rough rice and 40.5% after 60 min for brown rice for both cultivars. Rough rice required a longer soaking duration and attained a higher final MC because of the hull layer, which acts as a barrier that causes slower diffusion of water into the grain but retains more moisture (Indudhara Swamy et al 1971; Kar et al 1999; Thakur and Gupta 2006). Igathinathane et al (2005) reported that the leveling off of the moisture gain indicates that saturation MC has been reached. Because MC affects starch gelatinization degree, saturation MC was chosen in this study to reduce variation in starch gelatinization during the autoclaving step. Soaking times of 16 hr for rough rice and 90 min for brown rice for both cultivars were used in this study.

## Thermal Properties

Tables I and II summarize the peak melting temperatures ($T_p$) and enthalpies of transitions, respectively, of the treated rice samples. Starch was completely gelatinized during the parboiling treatment, as evidenced by the absence of native starch melting at approximately 70°C. Two endothermic transitions were observed in all parboiled samples. The first transition was melting of retrograded amylopectin with $T_p$ ranging from 58.9 to 61.6°C for cycle 1, from 57.4 to 63.6°C for cycle 2, and from 58.0 to 60.6°C for cycle 3 (Table I) and with enthalpy ranging from 1.4 to 3.7 J/g for cycle 1, from 4.0 to 6.5 J/g for cycle 2, and from 4.4 to 7.0 J/g for cycle 3 (Table II). The second transition was melting of AML complex with $T_p$ ranging from 114.4 to 118.7°C for cycle 1, from 115.4 to 120.4°C for cycle 2, and from 116.9 to 121.8°C for cycle 3 and with enthalpy ranging from 0.5 to 1.7 J/g for cycle 1, from 1.0 to 2.0 J/g for cycle 2, and from 0.5 to 1.5 J/g for cycle 3.

There was no clear trend for retrograded amylopectin $T_p$ between variables such as cultivar, feedstock, and storage cycle

**TABLE I**
**Peak Melting Temperatures of Retrograded Amylopectin and Amylose-Lipid (AML) Complex in Treated Rice Samples**

| | | | | Peak Melting Temperature (°C) | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Cycle 1[a] | | Cycle 2[b] | | Cycle 3[c] | |
| Cultivar | Feedstock | Final Product | Autoclaving Duration (min) | Retrograded Amylopectin | AML Complex | Retrograded Amylopectin | AML Complex | Retrograded Amylopectin | AML Complex |
| Wells | Rough | Brown | 20 | 60.2 ± 0.2 | 115.9 ± 0.1 | 57.8 ± 0.3 | 117.1 ± 0.3 | 60.6 ± 0.5 | 121.1 ± 1.1 |
| | | Milled | 20 | 60.5 ± 0.5 | 118.3 ± 0.1 | 57.4 ± 0.2 | 118.2 ± 1.2 | 58.7 ± 0.2 | 117.4 ± 0.5 |
| | Brown | Brown | 20 | 59.1 ± 0.2 | 115.5 ± 0.2 | 62.9 ± 0.6 | 116.3 ± 0.8 | 58.5 ± 0.2 | 116.9 ± 0.6 |
| | | Milled | 20 | 60.6 ± 0.7 | 115.6 ± 0.1 | 62.3 ± 0.4 | 116.7 ± 0.2 | 59.4 ± 0.3 | 118.5 ± 0.3 |
| | Rough | Brown | 40 | 59.4 ± 0.5 | 117.7 ± 0.3 | 59.9 ± 0.1 | 119.7 ± 0.1 | 59.1 ± 0.6 | 118.9 ± 0.2 |
| | | Milled | 40 | 61.1 ± 0.2 | 118.7 ± 0.1 | 57.9 ± 0.3 | 119.4 ± 0.1 | 59.3 ± 0.7 | 121.8 ± 1.4 |
| | Brown | Brown | 40 | 59.1 ± 0.2 | 114.7 ± 0.3 | 62.6 ± 0.4 | 118.3 ± 0.2 | 60.3 ± 0.3 | 119.3 ± 0.3 |
| | | Milled | 40 | 61.3 ± 0.3 | 118.4 ± 0.3 | 62.3 ± 0.8 | 117.7 ± 0.5 | 59.9 ± 0.4 | 119.4 ± 0.1 |
| XL723 | Rough | Brown | 20 | 61.0 ± 0.4 | 115.8 ± 0.4 | 58.4 ± 0.3 | 116.6 ± 0.3 | 58.4 ± 0.3 | 120.6 ± 0.3 |
| | | Milled | 20 | 60.7 ± 1.0 | 115.6 ± 0.9 | 58.6 ± 0.3 | 118.6 ± 0.1 | 60.4 ± 0.2 | 120.3 ± 0.2 |
| | Brown | Brown | 20 | 58.9 ± 0.2 | 114.4 ± 0.4 | 62.7 ± 0.5 | 115.4 ± 0.5 | 58.7 ± 0.4 | 117.7 ± 0.3 |
| | | Milled | 20 | 59.6 ± 0.4 | 115.2 ± 0.4 | 63.6 ± 0.4 | 117.7 ± 0.3 | 58.9 ± 0.7 | 118.1 ± 0.2 |
| | Rough | Brown | 40 | 61.6 ± 0.8 | 117.8 ± 1.5 | 59.4 ± 0.4 | 119.2 ± 0.1 | 59.1 ± 1.0 | 119.2 ± 0.9 |
| | | Milled | 40 | 61.0 ± 1.1 | 118.4 ± 0.2 | 59.1 ± 0.9 | 120.4 ± 0.8 | 60.3 ± 0.3 | 120.4 ± 0.1 |
| | Brown | Brown | 40 | 61.3 ± 0.3 | 115.3 ± 0.1 | 62.2 ± 0.3 | 116.3 ± 0.3 | 58.0 ± 0.4 | 117.5 ± 0.4 |
| | | Milled | 40 | 59.6 ± 0.3 | 114.5 ± 0.3 | 61.5 ± 0.3 | 115.4 ± 0.4 | 58.1 ± 0.3 | 119.5 ± 0.3 |

[a] Dried immediately after autoclaving at 120°C for 20 or 40 min.
[b] Autoclaved at 120°C for 20 or 40 min and then stored at room temperature for 24 hr.
[c] Autoclaved at 120°C for 20 or 40 min, stored at room temperature for 24 hr, autoclaved and stored again, and then dried.

**TABLE II**
**Enthalpies of Retrograded Amylopectin and Amylose-Lipid (AML) Complex in Treated Rice Samples**

| | | | | Enthalpy (J/g) | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Cycle 1[a] | | Cycle 2[b] | | Cycle 3[c] | |
| Cultivar | Feedstock | Final Product | Autoclaved Duration (min) | Retrograded Amylopectin | AML Complex | Retrograded Amylopectin | AML Complex | Retrograded Amylopectin | AML Complex |
| Wells | Rough | Brown | 20 | 1.9 ± 0.2 | 1.1 ± 0.1 | 5.3 ± 0.2 | 1.3 ± 0.1 | 7.0 ± 0.6 | 1.0 ± 0.2 |
| | | Milled | 20 | 2.1 ± 0.1 | 1.7 ± 0.2 | 5.5 ± 0.1 | 1.3 ± 0.3 | 5.7 ± 0.1 | 1.4 ± 0.1 |
| | Brown | Brown | 20 | 1.4 ± 0.3 | 0.8 ± 0.1 | 4.2 ± 0.2 | 1.0 ± 0.1 | 4.4 ± 0.1 | 1.1 ± 0.1 |
| | | Milled | 20 | 1.9 ± 0.1 | 0.9 ± 0.2 | 4.6 ± 0.2 | 1.3 ± 0.1 | 4.9 ± 0.2 | 1.2 ± 0.2 |
| | Rough | Brown | 40 | 2.3 ± 0.1 | 0.5 ± 0.1 | 5.7 ± 0.1 | 1.1 ± 0.1 | 5.8 ± 0.1 | 1.3 ± 0.1 |
| | | Milled | 40 | 2.6 ± 0.4 | 1.1 ± 0.3 | 5.9 ± 0.1 | 1.2 ± 0.1 | 5.3 ± 0.1 | 0.5 ± 0.1 |
| | Brown | Brown | 40 | 2.0 ± 0.2 | 1.1 ± 0.1 | 4.2 ± 0.2 | 2.0 ± 0.1 | 5.0 ± 0.2 | 1.4 ± 0.1 |
| | | Milled | 40 | 2.4 ± 0.2 | 1.3 ± 0.2 | 4.0 ± 0.1 | 1.9 ± 0.1 | 5.1 ± 0.1 | 1.5 ± 0.1 |
| XL723 | Rough | Brown | 20 | 2.9 ± 0.2 | 0.9 ± 0.1 | 6.4 ± 0.1 | 1.2 ± 0.1 | 5.4 ± 0.2 | 1.2 ± 0.1 |
| | | Milled | 20 | 2.1 ± 0.1 | 1.7 ± 0.2 | 5.3 ± 0.1 | 1.4 ± 0.1 | 5.6 ± 0.1 | 1.3 ± 0.1 |
| | Brown | Brown | 20 | 3.3 ± 0.2 | 0.7 ± 0.1 | 5.5 ± 0.2 | 1.0 ± 0.2 | 4.9 ± 0.3 | 0.9 ± 0.3 |
| | | Milled | 20 | 3.7 ± 0.1 | 1.0 ± 0.2 | 5.5 ± 0.2 | 1.3 ± 0.1 | 5.3 ± 0.3 | 1.2 ± 0.1 |
| | Rough | Brown | 40 | 2.3 ± 0.2 | 1.2 ± 0.1 | 6.4 ± 0.3 | 1.0 ± 0.1 | 6.9 ± 0.3 | 1.2 ± 0.2 |
| | | Milled | 40 | 2.3 ± 0.2 | 0.9 ± 0.1 | 6.5 ± 0.1 | 1.4 ± 0.2 | 6.7 ± 0.2 | 1.0 ± 0.1 |
| | Brown | Brown | 40 | 2.8 ± 0.3 | 1.0 ± 0.1 | 5.5 ± 0.1 | 1.0 ± 0.1 | 5.6 ± 0.1 | 1.4 ± 0.1 |
| | | Milled | 40 | 2.2 ± 0.1 | 0.8 ± 0.2 | 5.4 ± 0.3 | 1.3 ± 0.1 | 5.8 ± 0.1 | 1.1 ± 0.1 |

[a] Dried immediately after autoclaving at 120°C for 20 or 40 min.
[b] Autoclaved at 120°C for 20 or 40 min and then stored at room temperature for 24 hr.
[c] Autoclaved at 120°C for 20 or 40 min, stored at room temperature for 24 hr, autoclaved and stored again, and then dried.

(Table I). The only trend noted was that brown rice as feedstock had generally higher $T_p$ but lower enthalpy of retrograded amylopectin than rough rice as feedstock for both autoclaving durations in cycle 2 samples. In contrast, cycles 1 and 3 samples did not exhibit this trend, which was attributed to the immediate drying in cycle 1 and the repeated autoclaving in cycle 3. The repeated autoclaving probably destroyed the amylopectin crystals with a higher $T_p$ to result in crystalline structure with a lower $T_p$.

The $T_p$ of AML complex generally increased from cycle 1 to cycle 2 to cycle 3. There are two thermally distinct forms of AML complexes (I with low $T_p$ and II with high $T_p$), and their formation depends on the crystallization conditions, for example, temperature and lipid type (Biliaderis and Galloway 1989). Complex I is formed under rapid nucleation with low $T_p$ of 90–100°C; complex II is the preferred form at high crystallization temperature with $T_p$ of 110–120°C. An increase in $T_p$ indicates improved stability of the structure. In this study, the AML complex in parboiled rice was a more stable complex II form. The slightly higher AML complex $T_p$ in samples prepared from rough rice as feedstock was attributed to the long soaking time (16 hr) that promoted the migration of lipids from the bran layer to the endosperm and the formation of more stable structure as a result of annealing. The process of reautoclaving could melt the unstable structure to become more stable upon cooling. Similarly, an autoclaving duration of 40 min could lead to a higher $T_p$ because it facilitated the melting and reforming of AML crystalline structure.

Retrograded amylose, which is characterized by its $T_p$ above 120°C (Biliaderis and Tonogai 1991), was not observed in this study; this result is similar to that obtained by Ong and Blanshard (1995). Parboiled rice samples may contain retrograded amylose, but it may be in small amounts and undetectable (Sievert and Pomeranz 1990).

The storage treatment greatly increased amylopectin retrogradation, as shown by a significant increase of retrograded amylopectin enthalpy from cycle 1 to cycle 2. A similar trend of increasing retrogradation with storage was also reported by Niba (2003) and Vandeputte et al (2003). However, repeated autoclaving and storage (cycle 3) did not further increase amylopectin retrogradation as compared with cycle 2. The presence of retrograded amylopectin in cycle 1 samples, which were dried immediately without the storage treatment, indicates that a significant amount of amylopectin also retrograded rapidly after gelatinization. Cultivar XL723 and rough rice as feedstock were found generally to produce larger amounts of retrograded amylopectin in cycle 2.

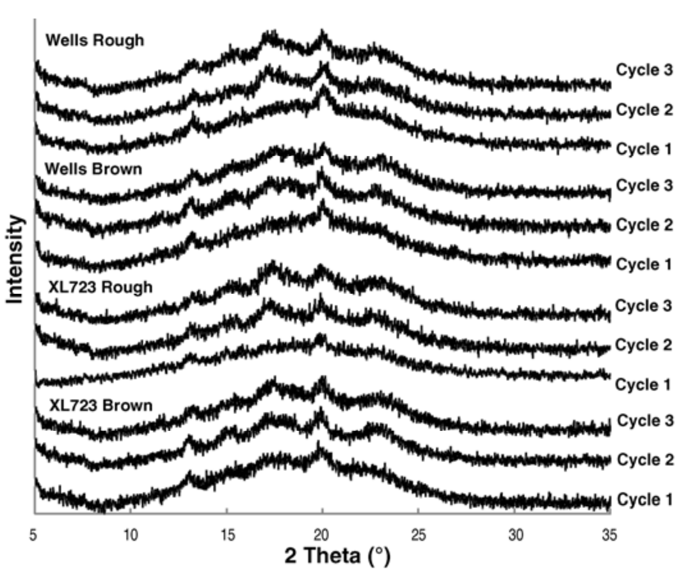


**Fig. 2.** X-ray diffraction patterns of parboiled rice flour samples from Wells and XL723 with rough and brown rice as feedstocks and milled rice as the finished product. Treatment cycle 1 was dried immediately after autoclaving at 120°C for 20 min; cycle 2 was autoclaved at 120°C for 20 min and then stored at room temperature for 24 hr; cycle 3 was autoclaved at 120°C for 20 min, stored at room temperature for 24 hr, autoclaved and stored again, and then dried.

Biliaderis and Juliano (1993) reported that the parboiling conditions of soaking and autoclaving developed, and with storage (cycle 2) reinforced, the formation of AML complex. Nevertheless, repeated autoclaving and storage (cycle 3) did not create additional AML complex and even decreased AML complex formation for some samples. However, because of sample variation, no definite conclusion can be drawn on the effects of cultivar, feedstock, and autoclave duration on the formation of AML complex, which was also reported on by Larsen et al (2000).

### X-Ray Diffraction

The X-ray diffraction patterns for treated milled rice flours are shown in Figure 2. The X-ray patterns of treated brown rice flours are not included because they displayed patterns similar to the milled rice flours. All samples showed peaks at 2Θ = 13.5, 17, 20, and 22.6°, indicating a mixture of B- and V-type diffraction patterns associated with retrograded starch and AML complex (Mahanta et al 1989). Generally, the intensity of the peaks increased from cycle 1 to cycle 2 to cycle 3. The peaks at 2Θ = 17 and 22.6° were weak for all cycle 1 samples and became stronger in cycles 2 and 3 samples. The peak at 2Θ = 15.3° was noted in some cycle 2 and 3 samples. The increases in peak intensities were supported by the increase in melting enthalpy of retrograded amylopectin and AML complex (Table II). Rough rice as feedstock generally showed higher peak intensity than brown rice as feedstock, a result that also corresponded to the higher enthalpies of retrograded amylopectin and AML complex in rough rice samples (Table II).

### Pasting Properties

The pasting properties of native Wells and XL723 are summarized in Table III, and the pasting profiles of parboiled rice samples from Wells and XL723 are shown in Figures 3 and 4, respectively. The native states of both cultivars displayed very high peak viscosity, large breakdown, and significant setback values. Milled rice had higher pasting viscosities than brown rice, a result that was ascribed to the higher starch content in milled rice. XL723 had higher pasting viscosities than Wells in both native and parboiled states, presumably because of its lower amylose content. The parboiling and storage treatments not only significantly decreased the pasting viscosity but also changed the pasting profile to little breakdown in all parboiled rice samples for both cultivars; these results agreed with previous reports (Raghavendra Rao and Juliano 1970; Ali and Bhattacharya 1980; Himmelsbach et al 2008). The initial viscosity of approximately 100 cP was high because starch was gelatinized during parboiling; therefore, parboiled rice hydrated and solubilized more than the same native rice at low temperatures (Bhattacharya 1985).

For both cultivars, parboiled rice from cycle 1 produced the highest pasting viscosity, followed by cycle 2, whereas cycle 3 samples showed low pasting viscosity. The repeated autoclaving

**TABLE III**
**Pasting Properties of Native Wells and XL723 as Measured by a Rapid Visco Analyser**

| Cultivar | Final Product | Viscosity (cP) Peak | Trough | Breakdown | Final | Setback |
|---|---|---|---|---|---|---|
| Wells | Brown | 2277 | 980 | 1297 | 2264 | 1284 |
| | Milled | 3142 | 1342 | 1800 | 2817 | 1475 |
| XL723 | Brown | 2481 | 1068 | 1413 | 2250 | 1182 |
| | Milled | 3568 | 1429 | 2139 | 2801 | 1372 |

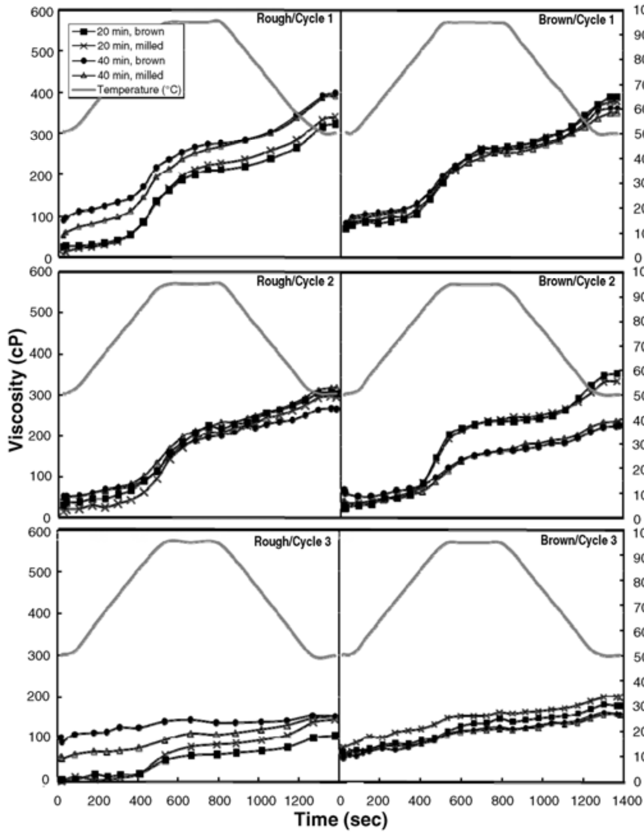


**Fig. 3.** Pasting profile of parboiled rice flour samples from Wells with rough and brown rice as feedstocks and milled rice as the finished product. Treatment cycle 1 was dried immediately after autoclaving at 120°C for 20 min; cycle 2 was autoclaved at 120°C for 20 min and then stored at room temperature for 24 hr; cycle 3 was autoclaved at 120°C for 20 min, stored at room temperature for 24 hr, autoclaved and stored again, and then dried.

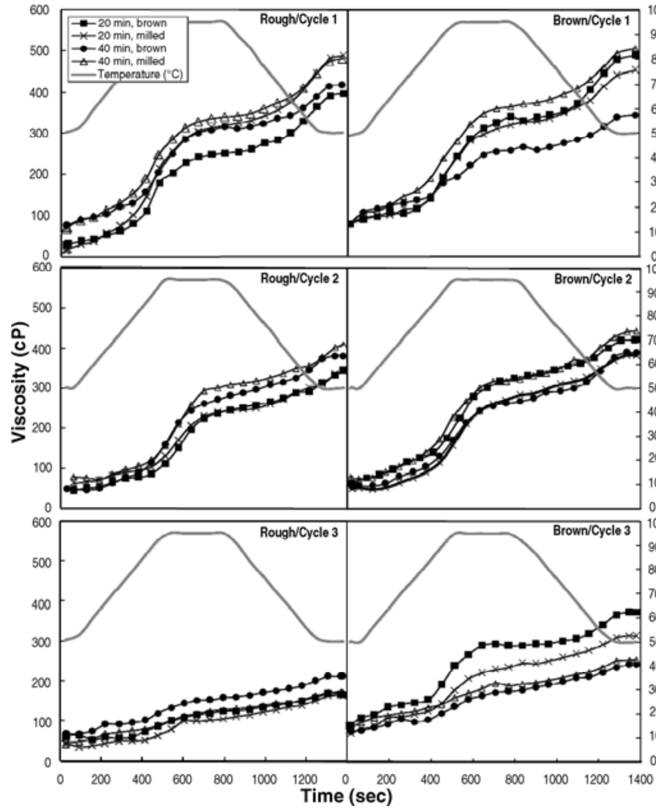


**Fig. 4.** Pasting profile of parboiled rice flour samples from XL723 with rough and brown rice as feedstocks and milled rice as the finished product. Treatment cycle 1 was dried immediately after autoclaving at 120°C for 20 min; cycle 2 was autoclaved at 120°C for 20 min and then stored at room temperature for 24 hr; cycle 3 was autoclaved at 120°C for 20 min, stored at room temperature for 24 hr, autoclaved and stored again, and then dried.

treatment significantly decreased the pasting viscosity, and autoclaving for 40 min was more effective in reducing pasting viscosity than autoclaving for 20 min; these results agree with those of Ali and Bhattacharya (1980) that rice pasting viscosity decreased with increasing severity of the heat treatment during parboiling. Although parboiled rice samples did not show great differences in their thermal properties between cycles 2 and 3 (Tables I and II), the lower pasting viscosity of cycle 3 samples relative to cycle 2 samples might be attributed to the increased starch-protein interaction from disruption of protein bodies (Raghavendra Rao and Juliano 1970) and the increase in $T_p$ of AML complex in cycle 3, which further restricted starch swelling.

**Starch Fractions**

The starch fractions as affected by parboiling and storage of both rice cultivars are shown in Table IV. Starch fractions were expressed as percent of total dry starch for ease of comparison because brown rice contains less starch than milled rice. RDS ranged from 81.7 to 95.3% for cycle 1, from 76.9 to 89.3% for cycle 2, and from 79.6 to 88.7% for cycle 3. Cultivar Wells tended to have a slightly lower RDS than XL723. In general, RDS levels decreased and SDS and RS levels increased with the storage treatment, as evidenced from their values in cycle 1 vs. cycle 2. Rice stored at room temperature became more resistant to enzymatic degradation (Eerlingen et al 1994; Fredriksson et al 2000; Frei et al 2003). Niba (2003) also showed an increase in SDS levels with storage and an inverse relationship between SDS and RDS levels. Rough rice as a feedstock tended to produce lower RDS levels but higher SDS levels in cycle 1 samples than brown rice as feedstock, but no clear trend on feedstock effect was noted for cycles 2 and 3. Autoclaving duration of 40 min generally produced lower RDS levels and higher SDS levels than autoclaving duration of 20 min.

A significant negative relationship between the fat and protein content in foods and the GI has been reported (Jenkins et al 1981). Therefore, chemical analyses presented in this study may not reveal all the impacts from the treatments on starch fractions because of the complex nature of interactions from gelatinized and disorganized starch, starch and nonstarch lipids, and disrupted protein bodies during parboiling, which rendered starch slowly digestible or indigestible but were not characterized in this study. For example, the protein fractions were less extractable from parboiled rice (Raghavendra Rao and Juliano 1970), which might form strong interactions with starch and limit the accessibility of amylolytic enzymes to starch.

**Statistical Analysis**

The effects of parboiling variables and storage treatment on starch fractions and the correlations between SDS and retrograded amylopectin enthalpy and between RS and AML complex were statistically analyzed. Statistically, cultivar and storage significantly affected all starch fractions (Table V), whereas final product (milled vs. brown rice) was not a significant factor affecting starch fractions. Autoclaving duration had impacts on RDS and SDS. Interactions of cultivar × final product, cultivar × autoclaving × final product, feedstock × autoclaving × storage, and cultivar × autoclaving × final product × storage also had significant impacts on all three starch fractions. These results show that cultivar and the storage treatment were the important factors affecting the starch fractions in parboiled rice. The highest level of interac-

TABLE IV
**Percentage of Rapidly Digestible Starch (RDS), Slowly Digestible Starch (SDS), and Resistant Starch (RS) in Treated Rice Samples**

| Cultivar | Feedstock | Final Product | Autoclaving Duration (min) | Percentage (%) Cycle 1[a] RDS | SDS | RS | Cycle 2[b] RDS | SDS | RS | Cycle 3[c] RDS | SDS | RS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Wells | Rough | Brown | 20 | 86.6 ± 3.8 | 3.5 ± 2.6 | 9.9 ± 2.6 | 84.6 ± 1.1 | 5.8 ± 2.6 | 9.5 ± 3.5 | 85.5 ± 3.2 | 10.1 ± 2.4 | 4.3 ± 1.5 |
| | | Milled | 20 | 81.7 ± 3.0 | 6.3 ± 4.0 | 12.0 ± 2.2 | 82.7 ± 4.0 | 11.0 ± 3.8 | 6.3 ± 2.8 | 83.1 ± 1.9 | 14.8 ± 1.9 | 2.2 ± 1.2 |
| | Brown | Brown | 20 | 93.1 ± 0.8 | 2.3 ± 1.2 | 4.7 ± 1.4 | 86.5 ± 2.3 | 6.9 ± 1.8 | 6.6 ± 1.8 | 82.0 ± 1.6 | 10.3 ± 1.6 | 7.7 ± 4.1 |
| | | Milled | 20 | 90.0 ± 1.9 | 5.1 ± 1.5 | 4.9 ± 1.9 | 82.6 ± 1.4 | 14.9 ± 1.9 | 2.5 ± 1.9 | 83.9 ± 3.5 | 10.5 ± 3.5 | 5.6 ± 1.4 |
| | Rough | Brown | 40 | 85.8 ± 1.8 | 11.7 ± 1.9 | 2.5 ± 1.6 | 81.6 ± 3.9 | 14.4 ± 1.3 | 3.9 ± 1.3 | 84.3 ± 3.4 | 8.0 ± 3.4 | 7.7 ± 3.8 |
| | | Milled | 40 | 87.1 ± 3.6 | 11.0 ± 4.2 | 1.9 ± 1.8 | 80.7 ± 1.6 | 16.8 ± 0.4 | 2.5 ± 0.4 | 85.4 ± 2.6 | 8.6 ± 2.6 | 6.0 ± 1.1 |
| | Brown | Brown | 40 | 88.1 ± 1.2 | 1.0 ± 0.5 | 11.0 ± 1.1 | 86.6 ± 1.7 | 7.4 ± 0.9 | 6.1 ± 0.9 | 82.6 ± 1.9 | 14.7 ± 1.9 | 2.7 ± 1.4 |
| | | Milled | 40 | 88.8 ± 3.3 | 4.7 ± 1.9 | 6.5 ± 1.8 | 84.0 ± 2.8 | 7.1 ± 4.0 | 8.9 ± 4.0 | 79.6 ± 2.3 | 10.1 ± 2.3 | 10.3 ± 4.2 |
| XL723 | Rough | Brown | 20 | 87.2 ± 3.5 | 3.3 ± 1.0 | 9.4 ± 3.2 | 84.2 ± 1.8 | 8.6 ± 3.1 | 7.2 ± 2.6 | 84.4 ± 4.2 | 9.9 ± 4.3 | 5.7 ± 0.5 |
| | | Milled | 20 | 90.2 ± 3.7 | 4.7 ± 3.0 | 5.1 ± 4.9 | 89.3 ± 4.0 | 6.6 ± 2.1 | 4.1 ± 2.1 | 86.4 ± 2.5 | 7.4 ± 1.9 | 6.2 ± 1.6 |
| | Brown | Brown | 20 | 90.6 ± 3.0 | 3.9 ± 2.0 | 5.5 ± 1.9 | 89.1 ± 2.1 | 8.4 ± 2.4 | 2.5 ± 2.4 | 88.7 ± 4.2 | 10.6 ± 4.3 | 0.7 ± 0.5 |
| | | Milled | 20 | 95.3 ± 0.9 | 1.0 ± 0.5 | 3.7 ± 1.1 | 83.7 ± 2.4 | 8.1 ± 2.5 | 8.2 ± 2.5 | 87.9 ± 0.2 | 4.7 ± 2.2 | 7.4 ± 2.5 |
| | Rough | Brown | 40 | 92.8 ± 2.8 | 5.5 ± 1.9 | 1.7 ± 1.7 | 81.0 ± 2.7 | 10.1 ± 1.4 | 8.8 ± 1.4 | 81.6 ± 3.3 | 10.5 ± 2.1 | 7.9 ± 2.4 |
| | | Milled | 40 | 82.9 ± 0.8 | 16.2 ± 1.1 | 0.9 ± 0.3 | 76.9 ± 2.1 | 17.2 ± 4.9 | 5.9 ± 4.9 | 82.0 ± 1.7 | 10.3 ± 1.7 | 7.7 ± 1.4 |
| | Brown | Brown | 40 | 90.7 ± 2.9 | 4.5 ± 3.7 | 4.8 ± 1.4 | 89.3 ± 1.6 | 2.4 ± 1.4 | 8.4 ± 1.4 | 80.5 ± 0.8 | 13.5 ± 1.8 | 6.0 ± 2.5 |
| | | Milled | 40 | 90.2 ± 3.7 | 3.7 ± 1.9 | 6.2 ± 1.9 | 79.0 ± 2.7 | 15.2 ± 1.3 | 5.8 ± 1.3 | 81.4 ± 1.0 | 11.3 ± 2.7 | 7.3 ± 2.6 |

[a] Dried immediately after autoclaving at 120°C for 20 or 40 min.
[b] Autoclaved at 120°C for 20 or 40 min and then stored at room temperature for 24 hr.
[c] Autoclaved at 120°C for 20 or 40 min, stored at room temperature for 24 hr, autoclaved and stored again, and then dried.

TABLE V
**Statistical Analysis of Treatments and Their Interactions on Starch Fractions and Enthalpies[a]**

| Factors | Probability > *F* RDS | SDS | RS |
|---|---|---|---|
| Cultivar (C) | <0.0001* | <0.0001* | 0.0403* |
| Feedstock (FS) | 0.0016* | 0.7198 | 0.0023* |
| Autoclaving duration (AD) | <0.0001* | <.0001* | 0.9334 |
| Final product (FP) | 0.2626 | 0.1743 | 0.8309 |
| Storage (S) | <0.0001* | <.0001* | 0.0044* |
| C × FS | 0.8107 | 0.4359 | 0.2828 |
| C × AD | <0.0001* | <0.0001* | 0.0859 |
| FS × AD | 0.0584 | 0.0018* | <0.0001* |
| C × FS × AD | 0.0761 | 0.6726 | 0.0117* |
| C × FP | 0.0121* | <0.0001* | 0.0146* |
| FS × FP | 0.7811 | 0.0927 | 0.0398* |
| C × FS × FP | 0.0356* | 0.8555 | 0.014* |
| AD × FP | 0.6348 | 0.4416 | 0.6391 |
| C × AD × FP | <0.0001* | <0.0001* | 0.0192* |
| FS × AD × FP | 0.0704 | 0.2055 | 0.6439 |
| C × FS × AD × FP | 0.0009* | 0.3062 | 0.0162* |
| C × S | 0.8917 | 0.077 | 0.1687 |
| FS × S | <0.0001* | 0.0662 | 0.0005* |
| C × FS × S | 0.0026* | 0.8463 | 0.0004* |
| AD × S | 0.4508 | 0.0039* | <0.0001* |
| C × AD × S | 0.0022* | 0.2528 | 0.0675 |
| FS × AD × S | 0.0015* | <.0001* | <0.0001* |
| C × FS × AD × S | 0.0017* | 0.7414 | <0.0001* |
| FP × S | 0.0594 | 0.0037* | 0.2987 |
| C × FP × S | 0.0065* | 0.3157 | <0.0001* |
| FS × FP × S | 0.0311* | 0.0178* | 0.4111 |
| C × FS × FP × S | 0.2332 | 0.2538 | 0.9437 |
| AD × FP × S | 0.3496 | 0.289 | 0.5436 |
| C × AD × FP × S | <0.0001* | <0.0001* | <0.0001* |
| FS × AD × FP × S | 0.0547 | 0.2988 | 0.5125 |
| C × FS × AD × FP × S | 0.9242 | 0.1351 | 0.0963 |

[a] Numbers marked with an asterisk (*) are statistically significant at $P \leq 0.05$. RDS = rapidly digestible starch, SDS = slowly digestible starch, and RS = resistant starch.

tion was a four-way interaction between cultivar, autoclaving, final product, and storage.

The correlations between SDS and retrograded amylopectin enthalpy and between RS and AML complex were significant and positively correlated (Table VI). RDS was negatively correlated with SDS and RS, which was also reported by Niba (2003). The results show that enthalpies of retrograded amylopectin and AML complex may be used as indicators for SDS and RS contents, respectively, in parboiled rice.

TABLE VI
**Correlation Matrix for Data on Starch Fractions and Enthalpies[a]**

| | RDS | SDS | RS | Retrograded Amylopectin Enthalpy |
|---|---|---|---|---|
| RDS | … | … | … | … |
| SDS | –0.72* | … | … | … |
| RS | –0.35* | –0.39* | … | … |
| Retrograded amylopectin enthalpy | –0.41* | 0.4* | 0 | … |
| Amylose-lipid complex enthalpy | –0.26* | 0.14 | 0.18* | 0.14 |

[a] Numbers marked with an asterisk (*) are statistically significant at $P \leq 0.05$. RDS = rapidly digestible starch, SDS = slowly digestible starch, and RS = resistant starch.

## CONCLUSIONS

Both cultivar and parboiling process, and their interactions, affected the amounts of starch fractions in parboiled rice. Parboiling variables, including feedstock, autoclaving duration, and storage treatment, had impacts on the formation of starch fractions, whereas final product as brown rice or milled rice had little impact. The storage treatment promoted the formation of SDS and decreased RDS content in parboiled rice. When the resultant parboiled rice was dried immediately without the additional storage and repeated autoclaving treatments, rough rice as feedstock produced more SDS but less RDS, and rough rice produced more RS at 20-min autoclaving but brown rice produced more RS at 40-min autoclaving. It is possible to increase the health benefits of parboiled rice by choosing cultivars and the combination of parboiling conditions that promote the formation of SDS and RS by encouraging the formation of retrograded amylopectin and AML complex and the interactions among rice components.


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