Functional Properties as Affected by Laboratory-Scale Parboiling of Rough Rice and Brown Rice

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ABSTRACT: Rough rice (RR) is the conventional feedstock for parboiling. The use of brown rice (BR) instead of RR is gaining interest because it results in shorter processing time and lower energy requirement. This study compared the functional properties of milled parboiled rice under different parboiling conditions from RR and BR. Presoaked RR and BR from cultivars Bolivar, Cheniere, Dixiebelle, and Wells were parboiled under mild (20 min, 100 °C, 0 kPa) and severe (20 min, 120 °C, 98 kPa) laboratory-scale conditions. Head rice yield improved on the RR and BR samples subjected to severe parboiling and was comparable to that of a commercially parboiled sample. Mild parboiling of BR resulted in lower head rice yields. Parboiling generally resulted in decreased head rice whiteness, decreased apparent amylose, increased total lipid, and sparingly changed protein content. Under the same parboiling conditions, the extent of starch gelatinization was higher for BR compared to RR as manifested by some distinct differences in pasting and thermal properties. The cooking characteristics (water uptake ratio, leached materials, and volumetric expansion) and cooked rice texture (hardness and stickiness) of RR and BR subjected to severe parboiling were fairly comparable. Differences in parboiled rice functional properties due to cultivar effect were evident.

Keywords: brown rice, milling, parboiling, rough rice, starch gelatinization

Introduction

Rice that has been subjected to hydrothermal treatment prior to milling is termed parboiled rice. Traditional parboiling involves soaking in cold water, steaming, and drying (Bhattacharya 2004). However, pressure and warmer soaking temperature are commonly employed in modern processes to reduce processing time. More recently, the use of fluidization techniques (Soponronnarit and others 2006) and ohmic heating (Sivashanmugam and Arivazhagan 2008) to parboil rice have been reported. Parboiled rice accounts for about 15% of the world's milled rice (Bhattacharya 2004), and its market has been increasing especially in industrialized countries (Efferson 1985). It is the staple food in southern Asian countries such as India, Sri Lanka, Pakistan, Nepal, and Bangladesh (Juliano and Hicks 1996; Bhattacharya 2004; Roy and others 2007). It belongs to the most popular rice products in Europe including Belgium, Germany, Italy, and Spain (Efferson 1985; Bhattacharya 2004; Fuhlbrügge 2004; Vegas 2008). There is also a high demand for parboiled rice in Saudi Arabia, Turkey, Jamaica, Yemen, Ghana, and Nigeria (Otegbayo and others 2001; Bhattacharya 2004; Tomlins and others 2005; Vegas 2008).

Parboiling is accompanied by some profound changes in rice physical, chemical, and functional properties. Starch granules undergo irreversible swelling and fusion as a result of gelatinization (Rao and Juliano 1970; Ali and Bhattacharya 1980; Juliano and Hicks 1996). Protein bodies are disrupted (Rao and Juliano 1970) and protein barriers are inferred to form through disulfide cross-linking (Derycke and others 2005). Lipids form complexes with amylose, which, along with protein barriers, may contribute to restricted swelling and solubilization of starch during cooking (Biliaderis and others 1993; Derycke and others 2005). Parboiling also results in inward diffusion of water-soluble vitamins and other bran components (Juliano and Hicks 1996). Such changes in chemical components during parboiling, in turn, contribute to harder kernels upon drying, improved milling yields, more translucent but amber-colored head rice, firmer and less sticky cooked rice, higher retention of minerals and water-soluble vitamins, increased health-promoting starch fraction (resistant starch), and longer shelf life (Pedersen and others 1989; Juliano and Hicks 1996; Kar and others 1999; Otegbayo and others 2001; Bhattacharya 2004; Derycke and others 2005; Heinemann and others 2005; Kim and others 2006). Parboiled rice is most often used in the industrial and food service markets because of its ease of preparation, durability, and stability to overcooking (Juliano and Hicks 1996; Vegas 2008). It does well in canned and frozen foods, like soups, puddings, and dinners. Most restaurants in the United States serve parboiled rice (Vegas 2008).

The traditional feedstock for parboiling is rough rice (RR) or paddy. The siliceous hulls in RR, however, have a poor thermal conductivity and slow down heat transfer to the endosperm (Kar and others 1999). This makes RR parboiling more time and heat energy consuming. Hence, brown rice (BR) (dehulled rice) parboiling has become an attractive alternative. A shift to BR parboiling has been reported in recent years (Kar and others 1999; Bhattacharya 2004; Fuhlbrügge 2004; Soponronnarit and others 2006). It is estimated that parboiling BR can save about 40% of energy consumption compared with parboiling RR (Kar and others 1999; Soponronnarit and others 2006).

The consequences of parboiling treatment on the behavior of rice on cooking and other end-use applications are important and merit some thorough investigations. The functional properties of milled rice obtained from parboiling RR and BR need to be clearly

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documented; hence, this study was undertaken. There is also a need to develop a laboratory-scale parboiling procedure that will yield a product whose functional properties are close to those commercial samples parboiled at a plant scale.

Materials and Methods

Materials

Dried RR and BR samples (with moisture content of approximately 12%) from cultivars Bolivar, Cheniere, Dixiebelle, and Wells (2004 cropping year) were used in this study. Bolivar, Cheniere, and Dixiebelle were provided by the USDA-ARS in Beaumont (Tex., U.S.A.) and Wells by the Univ. of Arkansas Rice Processing Program (Fayetteville, Ark., U.S.A.). A commercially parboiled RR sample was obtained from Riceland Foods Inc. (Stuttgart, Ark., U.S.A), as reference. Samples were stored at 4 °C until analyzed.

Parboiling experiment

A 200 g rice sample (RR or BR) placed in a 1-L beaker was added with 600 mL of deionized water preheated at 65 °C. The sample was incubated in a water bath at 65 °C for 2 h. After soaking, water was drained through a strainer; the soaked sample was transferred into a 400-mL beaker, and then autoclaved (Office pressure sterilizer Model 8816A, AMSCO, Erie, Pa., U.S.A.). The following conditions were used in the autoclave: 20 min, 100 °C, 0 kPa for mild parboiling, and 20 min, 120 °C, 98 kPa (approximately 1 kg/cm^2) for severe parboiling. The autoclaved sample was spread evenly on a 40 × 30 cm meshed tray and then dried in an EMC (equilibrium moisture content) chamber (Model AA60-PF, RSP Industries Inc., Brooklyn, N.Y., U.S.A.) at 25 °C and 40% relative humidity until around 12% moisture content.

Milling quality

Parboiled RR samples were shelled with a rice dehuller (Satake THU-35, Satake Corp., Hiroshima, Japan), and then BR (100 g) was milled for 30 s in a friction mill (McGill Miller #2, Rapsco, Brookshire, Tex., U.S.A.). The resulting milled rice was separated into head rice and broken kernels on a double-tray shaker table (Grain-Man Machinery, Miami, Fla., U.S.A.) with 4.67 mm indentations on both trays. Total milled rice and head rice yields were calculated based on BR weight. The broken kernels were discarded and the head rice samples were cleaned in an aspirating device (Seedburo Equipment Co., Chicago, Ill., U.S.A.) to remove residual bran and other adhering particles. Cleaned head rice samples were placed in self-sealing plastic bags for use in succeeding tests. Head rice whiteness, in percent, was measured with a Kett C-300-3 whiteness meter (Kett Electric Lab., Tokyo, Japan) calibrated with a magnesium oxide standard plate that has a whiteness reading of 87.4%.

Head rice chemical composition

Head rice was ground into flour with a cyclone sample mill (Udy Corp., Fort Collins, Colo., U.S.A.) fitted with a 0.50 mm screen. Moisture content was determined by the AACC method 44-15A (AACC 2000). Duplicate 2-g samples were placed in dry aluminum moisture dishes and dried at 130 °C in a convection oven for 2 h. Crude protein content was measured by a micro-Kjeldahl apparatus according to AACC Method 46-13 (AACC 2000) using a 0.5 g sample and a factor of 5.95 for converting nitrogen content to protein. Milled rice surface total lipid was quantified by extraction with isopropyl alcohol according to the method of Lam and Proctor (2001). Apparent amylose content was determined by iodine colorimetry (Juliano and others 1981).

Pasting properties

The pasting characteristics of head rice flour slurries (3 g, 25 mL deionized water, 12% moisture basis) were determined with a Rapid Visco Analyser (RVA Series-4, Newport Scientific, Warriewood, NSW, Australia) using the AACC method 61-02 (AACC 2000). The slurry was heated from 50 to 95°C at a rate of 3 °C/min. A plot of paste viscosity in centipoise (cP) compared with time (minute) was used to determine peak, hot paste (trough), and final viscosity. Breakdown viscosity was calculated by subtracting hot paste viscosity from peak viscosity; setback viscosity was taken as final viscosity minus peak viscosity; and paste consistency as final viscosity minus hot paste viscosity.

Thermal properties

Thermal properties were evaluated with a Perkin-Elmer Pyris-1 differential scanning calorimeter (Perkin-Elmer Co., Norwalk, Conn., U.S.A.). The instrument was calibrated with indium and an empty pan was used as reference. Flour (approximately 4 mg) was weighed accurately into an aluminum pan and then moistened with 8 μL of deionized water using a microsyringe. The pan was hermetically sealed and allowed to stand for at least 1 h prior to analysis. Samples were heated from 25 to 130 °C at a rate of 10 °C/min. Gelatinization enthalpy, onset, peak, and conclusion temperatures were recorded. The percentage of gelatinized starch was calculated based on the change in enthalpy of the parboiled sample (ΔH_{par}) in comparison with the nonparboiled one (ΔH_{raw}), by the following equation (Marshall and others 1993):

$$\text{Gelatinized starch (\%)} = [1 - (\Delta H_{par}/\Delta H_{raw})] \times 100$$

Cooking characteristics and cooked rice texture

Samples were cooked in excess water. Five grams of head rice was weighed into a perforated basket (height = 7 cm and internal diameter = 4.2 cm). The basket was suspended in a long-type 150 mL beaker containing 100 mL of deionized water and allowed to stand for 10 min. The beaker was transferred into a home-style rice cooker with the inner pan containing 200 mL of deionized water, and then steam-cooked for 30 min. Six samples were cooked at a time. The beaker with the cooked sample was taken out and the excess water was allowed to drain for 5 min. The height of the cooked rice in the perforated basket was taken at 3 points with a sliding steel tape. The average of the 3 measurements was used in calculating cooked rice volume. Volumetric expansion was expressed as the quotient of cooked rice volume over head rice sample weight. The cooking water with leached materials left in the beaker was diluted to 100 mL in a volumetric flask and thoroughly mixed. A 50 mL aliquot was transferred into a dry, preweighed weighing boat and dried at 40 °C in a convection oven to constant weight. Percent leached material was calculated based on residue weight, cooking water total volume, and head rice weight.

Cooked rice samples were placed in separate self-sealing plastic bags and kept in a 1000-mL Dewar flask prior to texture analysis. Cooked rice texture was analyzed with a texture analyzer (Ta-XT2 Plus, Texture Technologies, Scarsdale, N.Y., U.S.A.) by a single compression method. Ten intact cooked rice kernels were placed on a flat aluminum plate (100-mm diameter) and were compressed to 90% of their original height using a 50-kg load cell. Crosshead speed, test speed, and posttest speed were set at 10, 5, and 0.5 mm/s, respectively. Texture data were obtained and processed with a Texture Exponent Software (Stable Microsystems, version 1.0.0.92, 2000, Surrey, England). The maximum compression force (N), required to press the kernels, was used as an indicator of cooked rice hardness while the adhesion energy (area under the curve, Ns), required to lift the compression plate, was used as an indicator for cooked rice stickiness. Measurements were repeated 6 times for each replicate sample.

Statistical analysis

The experiment was laid out on a completely randomized 4 × 5 factorial design, with cultivar (Bolivar, Cheniere, Dixiebelle, and Wells) and parboiling condition (no parboiling, mild/rough rice, mild/brown rice, severe/rough rice, and severe/brown rice) as main factors. The experiment was replicated twice. Analysis of variance (ANOVA) was used to evaluate the effects of the 2 factors and their interaction. Significantly different means were identified by Tukey's HSD (honestly significant differences) test. All statistical analyses were carried out using a JMP software version 7 (SAS Inst., Cary, N.C., U.S.A.)

Results and Discussion

Milling quality and color

The milling quality and whiteness of milled parboiled rice obtained by parboiling RR and BR are shown in Table 1. Total milled rice and head rice yields were expressed as percentages of BR weight. Total milled rice yield ranged 87.4% to 92.9% and was affected by both cultivar and parboiling treatment, although the interaction between these 2 factors was insignificant (Table 2). Total milled rice yield was generally higher for the batch subjected to severe parboiling conditions (both RR and BR); it was lower

Table 1—Milling quality and milled rice whiteness as affected by cultivar, parboiling condition, and cultivar–parboiling interaction.[A]

Cultivar	Parboiling condition/ feedstock	Milled rice (%)	Head rice (%)	Whiteness (%)
Bolivar	Control (no parboiling)	87.5 ± 0.5^{f}	68.0 ± 2.0^{i}	43.4 ± 0.2^{b}
	Mild/rough rice	89.4 ± 1.8^{cdef}	67.5 ± 0.7^{i}	32.4 ± 0.2^{g}
	Mild/brown rice	88.7 ± 1.5^{ef}	59.6 ± 0.8^{j}	30.8 ± 0.5^{h}
	Severe/rough rice	91.2 ± 1.9^{abc}	69.8 ± 0.7^{hi}	24.4 ± 0.2^{m}
	Severe/brown rice	90.9 ± 0.8^{bcde}	69.5 ± 0.3^{hi}	24.4 ± 0.1^{m}
Cheniere	Control (no parboiling)	88.8 ± 0.2^{def}	85.3 ± 1.8^{bc}	45.0 ± 0.3^{a}
	Mild/rough rice	91.0 ± 1.1^{bcd}	87.9 ± 0.3^{ab}	35.9 ± 0.1^{d}
	Mild/brown rice	93.3 ± 0.3^{a}	76.0 ± 2.8^{fg}	32.8 ± 0.1^{f}
	Severe/rough rice	92.8 ± 1.2^{ab}	87.6 ± 1.1^{ab}	29.4 ± 0.0^{j}
	Severe/brown rice	92.9 ± 1.3^{ab}	89.8 ± 2.0^{a}	28.8 ± 0.2^{k}
Dixiebelle	Control (no parboiling)	87.4 ± 0.2^{f}	72.8 ± 3.3^{gh}	44.9 ± 0.1^{a}
	Mild/rough rice	91.2 ± 0.5^{abc}	78.2 ± 1.3^{ef}	26.2 ± 0.1^{l}
	Mild/brown rice	91.2 ± 0.6^{abc}	72.7 ± 1.1^{gh}	29.9 ± 0.1^{1}
	Severe/rough rice	91.8 ± 0.9^{ab}	81.9 ± 2.8^{cd}	22.2 ± 0.1^{p}
	Severe/brown rice	92.7 ± 1.0^{ab}	80.1 ± 0.9^{de}	21.9 ± 0.2^{p}
Wells	Control (no parboiling)	89.4 ± 0.3^{cdef}	85.5 ± 1.8^{bc}	41.9 ± .1^{c}
	Mild/rough rice	91.2 ± 0.5^{abc}	87.8 ± 2.1^{ab}	33.4 ± 0.0^{e}
	Mild/brown rice	91.6 ± 1.4^{abc}	62.6 ± 0.3^{j}	30.2 ± 0.1^{i}
	Severe/rough rice	91.8 ± 1.5^{ab}	89.4 ± 1.7^{a}	23.7 ± 0.2^{n}
	Severe/brown rice	92.8 ± 0.5^{ab}	89.6 ± 1.2^{a}	22.6 ± 0.2°
Commercially parboiled sample		92.7 ± 0.4	87.6 ± 0.6	18.2 ± 0.2

[A]Means ± standard deviations from 2 replicates within a column having the same letter(s) are not significantly different at 5% level based on Tukey's honestly significant differences test.

Table 2—Analysis of variance (ANOVA) of parboiled milled rice properties as affected by cultivar, parboiling condition, and cultivar–parboiling interaction.

Property	Overall mean	Root mean square error (RMSE)	Prob > *F*		
			Cultivar (C)	Parboiling (P)	C × P
Total milled rice,%	90.88	1.04	0.0008*	<0.0001*	0.5356
Head rice,%	79.52	1.76	<0.0001*	<0.0001*	<0.0001*
Whiteness,%	31.20	0.11	<0.0001*	<0.0001*	<0.0001*
Apparent amylose,%	25.87	0.99	<0.0001*	<0.0003*	0.6334
Crude protein,%	7.59	0.24	<0.0001*	0.0375*	0.8068
Total lipid,%	0.63	0.04	<0.0001*	<0.0001*	0.0082*
Peak viscosity, cP	1753	40.73	<0.0001*	<0.0001*	<0.0001*
Final viscosity, cP	2564	44.39	<0.0001*	<0.0001*	<0.0001*
Paste breakdown, cP	408	33.08	<0.0001*	<0.0001*	<0.0001*
Setback viscosity, cP	811	34.01	<0.0001*	<0.0001*	<0.0001*
Paste consistency, cP	1220	40.00	<0.0001*	<0.0001*	<0.0001*
Onset GT, °C	77.08	0.18	<0.0001*	<0.0001*	<0.0001*
Peak GT, °C	80.90	0.20	<0.0001*	<0.0001*	<0.0001*
Conclusion GT, °C	85.97	0.59	<0.0001*	<0.0001*	0.1688
Gelat. enthalpy, J/g	8.09	0.12	<0.0001*	<0.0001*	0.0002*
% Starch gelatinization	21.22	1.04	<0.0001*	<0.0001*	<0.0001*
Water uptake ratio	2.14	0.05	<0.0001*	<0.0001*	<0.0001*
Vol. expansion, cm^3/g	5.10	0.21	0.0023*	<0.0001*	0.0050*
Leach material,%	4.59	0.32	<0.0001*	<0.0001*	<0.0001*
Hardness, N	69.72	2.20	<0.0001*	<0.0001*	0.0029*
Stickiness, N s	3.04	0.23	<0.0001*	<0.0001*	0.2206

*Statistically significant.

for the nonparboiled batch (control). Among cultivars, total milled rice was lower for Bolivar; the rest had a comparable total milled rice yield. Head rice yield ranged 59.6% to 89.8%, which is close to the range of 75% to 92% reported by Kar and others (1999) in parboiling BR. The reference sample (commercially parboiled RR) gave an average head rice yield of 87.6%. Head rice yield improved on parboiling except for the BR parboiled under mild conditions. Kar and others (1999) also observed a reduction in head rice yield in the parboiling of BR that involved soaking at 100 °C for 4 h and steaming for 10 min. The lower head rice yield of the BR parboiled under mild conditions was indicative of partial parboiling. Bhattacharya and Subba Rao (1966) reported that partially parboiled rice was more susceptible to breakage on milling. Chattopadhyay and Kunze (1986), likewise, found out that parboiled rice was also prone to fissure and may break like nonparboiled rice during milling because of the phenomenon known as moisture adsorption. The decrease in head rice yield observed in the mild parboiling of BR was not manifested on RR under the same parboiling conditions, possibly due to the protective effect of siliceous hulls against moisture adsorption.

Parboiled rice becomes discolored (turns light yellow to amber) due to Maillard type nonenzymatic browning and the diffusion of hull and bran pigments into the endosperm during soaking (Bhattacharya 2004; Lamberts and others 2006). In this study, the extent of milled rice discoloration was indicated by whiteness values. Whiteness ranged 18.2% to 35.9% for the parboiled, and 41.9% to 45% for the nonparboiled samples (Table 1). Based on whiteness values, milled parboiled rice color intensity has been classified as: parboiled dark (whiteness = 16% to 19.9%); parboiled medium (whiteness = 20% to 25.9%); and parboiled light (whiteness = 26% to 31%) (BNSI 2003). Color intensity values corresponding to parboiled light to parboiled medium were attained with the parboiling conditions used in this study. In contrast, the color intensity of the commercially parboiled sample used as reference was equivalent to parboiled dark. Parboiled medium was attained with severe parboiling conditions (except for Cheniere); and parboiled light with the mild parboiling conditions.

Physicochemical properties

Table 3 lists the apparent amylose, crude protein, and total lipid contents of the 4 rice cultivars as affected by laboratory-scale parboiling of BR and RR. Based on cultivar classes according to apparent amylose content (Juliano and others 1981), Bolivar, Dixiebelle, and Cheniere are high-amylose cultivars, whereas Wells is intermediate-amylose cultivar (Patindol and others 2007). Apparent amylose content decreased as a result of parboiling, regardless of whether RR or BR was used as a feedstock, and whether mild or severe conditions were employed. In a related study, Biswas and Juliano (1988) reported a mean 1% decrease in apparent amylose content on parboiling, and hot-water soluble amylose content decreased progressively with the severity of parboiling. The decrease in amylose content was attributed either to the leaching out of amylose into the soaking water, or by measurement errors owing to interference by milled rice surface lipids. Lipids reduce apparent amylose measurements by interfering the formation of blue amylose-iodine complex, which is the basis for the determination of amylose by iodine colorimetry (Juliano and others 1981). Surface total lipid (isopropyl alcohol extractable fraction) tended to increase, with the increase being more prevalent on the batches parboiled under severe conditions (for both RR and BR). Kato and others (1983) observed an increase in lipids bound to starch and protein and a decrease in unbound lipids due to parboiling. The results suggest that parboiling enhanced the interaction of bran lipids with endosperm starch and protein. This in turn, makes the lipid fraction of the aleurone layer more difficult to remove on milling. With the exception of Bolivar, crude protein was not significantly affected by parboiling, as its variation was mainly attributed to cultivar effect (Table 2). In contrast, Rao and Juliano (1970) reported a slight drop in protein content (by 0.05% to 0.37%) during parboiling, which were attributed to the leaching out of nonprotein nitrogen and albumin.

Pasting properties

Table 4 and Figure 1 demonstrate that parboiling caused a significant decrease in the paste viscosity parameters (peak, final,

Table 3—Some physicochemical properties of head rice as affected by cultivar, parboiling condition, and cultivar–parboiling interaction.[A]

Cultivar	Parboiling condition/ feedstock	Amylose (%)	Crude protein (%)	Total lipid (%)
Bolivar	Control (no parboiling)	28.7 ± 0.3[a]	9.1 ± 0.4[a]	0.30 ± 0.01[g]
	Mild/rough rice	25.9 ± 0.6[bc]	8.8 ± 0.2[ab]	0.50 ± 0.03[ef]
	Mild/brown rice	26.7 ± 0.4[b]	8.5 ± 0.2[b]	0.51 ± 0.01[def]
	Severe/rough rice	27.0 ± 0.4[b]	8.5 ± 0.1[b]	0.68 ± 0.03[bc]
	Severe/brown rice	26.5 ± 0.8[b]	8.6 ± 0.3[b]	0.76 ± 0.04[abc]
Cheniere	Control (no parboiling)	29.6 ± 0.3[a]	6.4 ± 0.1[cde]	0.35 ± 0.05[g]
	Mild/rough rice	27.0 ± 0.6[b]	6.6 ± 0.5[cde]	0.68 ± 0.05[bc]
	Mild/brown rice	26.9 ± 1.0[b]	6.2 ± 0.3[e]	0.70 ± 0.04[abc]
	Severe/rough rice	26.5 ± 0.9[b]	6.3 ± 0.3[de]	0.76 ± 0.02[abc]
	Severe/brown rice	26.3 ± 0.7[b]	6.2 ± 0.1[e]	0.84 ± 0.01[a]
Dixiebelle	Control (no parboiling)	28.3 ± 0.6[a]	8.9 ± 0.3[ab]	0.36 ± 0.06[fg]
	Mild/rough rice	26.0 ± 0.9[b]	8.7 ± 0.6[ab]	0.67 ± 0.03[bc]
	Mild/brown rice	26.5 ± 0.8[b]	8.7 ± 0.1[ab]	0.79 ± 0.09[abc]
	Severe/rough rice	25.8 ± 0.7[bc]	8.6 ± 0.7[ab]	0.78 ± 0.09[abc]
	Severe/brown rice	25.9 ± 1.1[bc]	8.5 ± 0.2[b]	0.82 ± 0.04[ab]
Wells	Control (no parboiling)	24.0 ± 0.6[cd]	6.8 ± 0.2[c]	0.38 ± 0.06[fg]
	Rough rice/mild	23.5 ± 0.8[de]	6.7 ± 0.3[cde]	0.66 ± 0.06[cd]
	Brown rice/mild	22.3 ± 0.5[de]	6.8 ± 0.1[cd]	0.67 ± 0.06[bc]
	Rough rice/severe	21.3 ± 0.2[e]	6.6 ± 0.2[cde]	0.65 ± 0.02[cde]
	Brown rice/severe	21.9 ± 0.5[de]	6.5 ± 0.1[cde]	0.84 ± 0.02[a]
Commercially parboiled sample		23.7 ± 0.3	7.7 ± 0.2	0.70 ± 0.04

[A]Means ± standard deviations from 2 replicates within a column having the same letter(s) are not significantly different at 5% level based on Tukey's honestly significant differences test.

breakdown, setback, and consistency) of head rice flour slurries. The decrease was affected by cultivar, parboiling condition, and cultivar–parboiling interaction (Table 2). Bolivar and Dixiebelle showed similar trend as regard to the change in pasting properties; that of Cheniere was similar to Wells. In terms of feedstock, BR samples parboiled under severe conditions generally showed the greatest decrease in paste viscosities. Bolivar and Dixiebelle BR parboiled under severe conditions did not show distinct peak viscosity, resulting in negative breakdown viscosity values. The decrease in paste viscosity as a result of parboiling was also reported in previous studies (Rao and Juliano 1970; Ali and Bhattacharya 1980; Biswas and Juliano 1988; Islam and others 2002; Soponronnarit and others 2006). Such decrease has been attributed to the decreased swelling ability and water-binding capacity of the partially gelatinized starch in parboiled rice (Ali and Bhattacharya 1980; Soponronnarit and others 2006).

Thermal properties

Differential scanning calorimetry has been used to quantify the thermal changes in parboiled rice and to correlate the results with final cooked rice quality and other functional properties (Biliaderis and others 1993; Ong and Blanshard 1995; Islam and others 2002;

Table 4—Pasting properties of head rice flours as affected by cultivar, parboiling condition, and cultivar–parboiling interaction.[A]

Cultivar	Parboiling condition/ feedstock	Peak viscosity (cP)	Final viscosity (cP)	Breakdown (cP)	Setback (cP)	Paste consistency (cP)
Bolivar	Control (no parboiling)	2734 ± 40[a]	4201 ± 11[a]	800 ± 50[c]	1468 ± 29[b]	2267 ± 21[a]
	Mild/rough rice	2374 ± 24[b]	4012 ± 18[b]	471 ± 57[de]	1638 ± 10[a]	1839 ± 64[b]
	Mild/brown rice	2382 ± 47[b]	3699 ± 14[c]	200 ± 13[gh]	1317 ± 61[c]	1788 ± 48[b]
	Severe/rough rice	1285 ± 38[f]	2200 ± 39[ef]	2 ± 5[i]	915 ± 10[de]	917 ± 10[f]
	Severe/brown rice	1144 ± 10[fg]	1888 ± 12[g]	−1 ± 4[i]	744 ± 13[fg]	744 ± 14[gh]
Cheniere	Control (no parboiling)	1866 ± 18[d]	2194 ± 11[ef]	878 ± 5[bc]	307 ± 10[lm]	1186 ± 10[de]
	Mild/rough rice	1978 ± 20[d]	2222 ± 10[e]	599 ± 55[d]	244 ± 21[m]	844 ± 35[fg]
	Mild/brown rice	1678 ± 25[e]	2178 ± 73[ef]	601 ± 14[d]	501 ± 48[jk]	1102 ± 62[e]
	Severe/rough rice	1090 ± 57[gh]	1574 ± 61[h]	198 ± 15[gh]	484 ± 10[jk]	682 ± 19[ghi]
	Severe/brown rice	816 ± 43[i]	1234 ± 13[i]	94 ± 6[hi]	418 ± 30[kl]	511 ± 24[j]
Dixiebelle	Control (no parboiling)	2784 ± 87[a]	4032 ± 25[ab]	996 ± 50[b]	1249 ± 62[c]	2246 ± 12[a]
	Mild/rough rice	2046 ± 11[cd]	3600 ± 10[c]	264 ± 12[fg]	1554 ± 11[ab]	1817 ± 10[b]
	Mild/brown rice	1570 ± 38[e]	2610 ± 78[d]	52 ± 6[i]	1039 ± 40[d]	1092 ± 47[e]
	Severe/rough rice	938 ± 10[hi]	1609 ± 25[f]	−8 ± 1[i]	671 ± 26[ghi]	679 ± 28[hi]
	Severe/brown rice	870 ± 62[i]	1442 ± 64[h]	−4 ± 3[i]	572 ± 10[hij]	576 ± 10[ij]
Wells	Control (no parboiling)	2390 ± 26[b]	2562 ± 87[d]	1174 ± 20[a]	171 ± 6[m]	1345 ± 41[cd]
	Mild/rough rice	2181 ± 33[c]	2721 ± 65[d]	816 ± 21[c]	540 ± 33[ijk]	1356 ± 12[c]
	Mild/brown rice	1982 ± 56[d]	2672 ± 10[d]	543 ± 5[d]	690 ± 59[fgh]	1233 ± 59[cde]
	Severe/rough rice	1716 ± 26[e]	2600 ± 35[d]	384 ± 94[ef]	883 ± 10[e]	1268 ± 73[cd]
	Severe/brown rice	1220 ± 52[fg]	2036 ± 58[fg]	98 ± 5[hi]	816 ± 12[ef]	913 ± 10[f]
Commercially parboiled sample		193 ± 5	294 ± 4	−1 ± 2	101 ± 0	100 ± 2

[A]Means ± standard deviations from 2 replicates within a column having the same letter(s) are not significantly different at 5% level based on Tukey's honestly significant differences test.

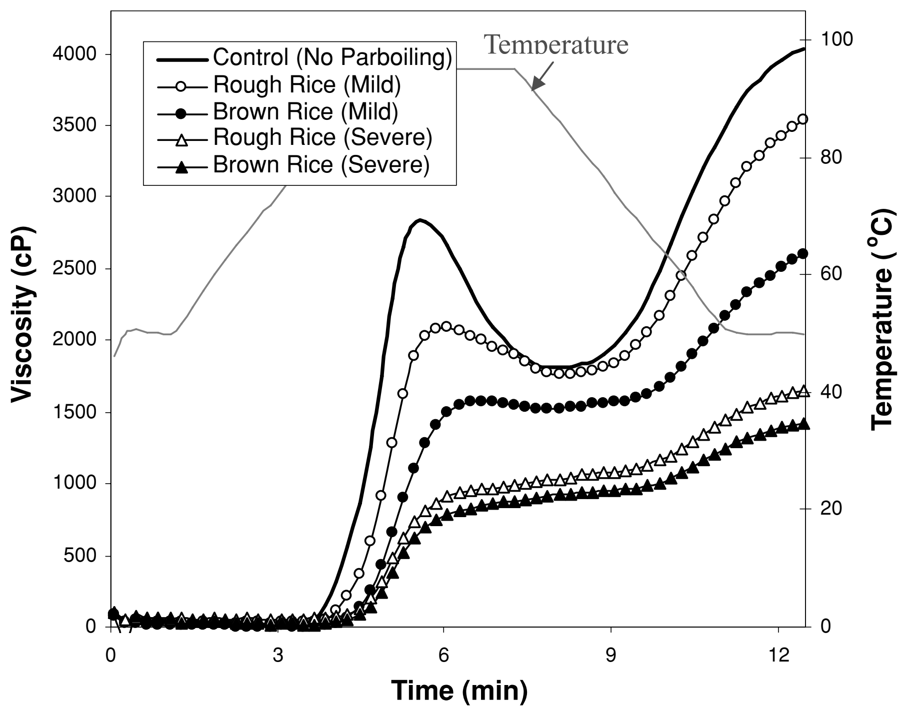

Figure 1—Pasting profiles of flour slurries from Dixiebelle head rice as affected by laboratory-scale parboiling treatment.

Table 5—Thermal properties of head rice flours as affected by cultivar, parboiling condition, and cultivar–parboiling interaction.[A]

Cultivar	Parboiling condition/ feedstock	Onset GT (°C)	Peak GT (°C)	Conclusion GT (°C)	Gelatinization enthalpy (J/g)	Gelatinized starch (%)
Bolivar	Control (no parboiling)	75.8 ± 0.2^{h}	78.7 ± 0.1^{h}	83.8 ± 0.2^{gh}	9.8 ± 0.1^{b}	00.0 ± 0.0^{g}
	Mild/rough rice	77.0 ± 0.3^{ef}	80.6 ± 0.3^{e}	85.4 ± 0.5^{ef}	8.5 ± 0.1^{c}	13.2 ± 0.6^{f}
	Mild/brown rice	77.4 ± 0.2^{ef}	80.7 ± 0.4^{de}	85.4 ± 0.6^{ef}	8.5 ± 0.1^{c}	13.4 ± 0.4^{ef}
	Severe/rough rice	80.4 ± 0.2^{bc}	84.0 ± 0.1^{ab}	88.8 ± 0.2^{ab}	6.8 ± 0.2^{f}	30.7 ± 2.0^{bc}
	Severe/brown rice	80.5 ± 0.2^{bc}	83.4 ± 0.1^{bc}	88.4 ± 0.4^{ab}	5.8 ± 0.1^{g}	40.6 ± 0.9^{a}
Cheniere	Control (no parboiling)	75.2 ± 0.2^{gh}	79.0 ± 0.3^{gh}	83.4 ± 0.3^{h}	10.3 ± 0.1^{ab}	00.0 ± 0.0^{g}
	Mild/rough rice	75.8 ± 0.2^{g}	79.4 ± 0.2^{gh}	83.7 ± 0.1^{gh}	8.4 ± 0.2^{c}	17.6 ± 1.4^{de}
	Mild/brown rice	77.3 ± 0.2^{ef}	80.6 ± 0.4^{e}	85.4 ± 0.2^{ef}	8.4 ± 0.1^{c}	18.0 ± 1.2^{d}
	Severe/rough rice	79.3 ± 0.2^{d}	82.9 ± 0.2^{c}	88.5 ± 0.4^{ab}	7.6 ± 0.0^{d}	26.5 ± 0.2^{c}
	Severe/brown rice	80.2 ± 0.2^{c}	83.6 ± 0.1^{bc}	88.2 ± 0.2^{bc}	6.2 ± 0.2^{g}	40.1 ± 2.1^{a}
Dixiebelle	Control (no parboiling)	75.3 ± 0.3^{gh}	79.6 ± 0.1^{fg}	84.7 ± 0.3^{fg}	10.5 ± 0.1^{a}	0.0 ± 0.0^{g}
	Mild/rough rice	77.8 ± 0.3^{e}	81.4 ± 0.2^{d}	87.0 ± 0.4^{cd}	8.4 ± 0.2^{c}	20.1 ± 0.7^{d}
	Mild/brown rice	77.3 ± 0.6^{ef}	81.5 ± 0.5^{d}	85.5 ± 0.3^{ef}	8.5 ± 0.0^{c}	19.4 ± 0.4^{d}
	Severe/rough rice	81.2 ± 0.1^{ab}	84.4 ± 0.3^{a}	89.2 ± 0.3^{ab}	6.9 ± 0.1^{ef}	34.2 ± 0.7^{b}
	Severe/brown rice	81.6 ± 0.2^{a}	84.8 ± 0.3^{a}	89.6 ± 0.8^{a}	6.3 ± 0.2^{g}	40.2 ± 1.2^{a}
Wells	Control (no parboiling)	71.0 ± 0.2^{k}	75.8 ± 0.2^{j}	82.2 ± 0.1^{i}	10.6 ± 0.2^{a}	00.0 ± 0.0^{g}
	Mild/rough rice	72.8 ± 0.3^{j}	77.6 ± 0.3^{i}	83.6 ± 0.2^{gh}	8.8 ± 0.1^{c}	17.0 ± 0.4^{def}
	Mild/brown rice	74.0 ± 0.2^{i}	78.8 ± 0.2^{h}	83.3 ± 0.2^{hi}	8.5 ± 0.2^{c}	19.3 ± 1.3^{d}
	Severe/rough rice	75.8 ± 0.2^{g}	80.3 ± 0.1^{ef}	86.3 ± 0.4^{de}	7.3 ± 0.2^{de}	31.1 ± 2.0^{b}
	Severe/brown rice	77.0 ± 0.2^{ef}	81.0 ± 0.3^{de}	87.0 ± 0.4^{cd}	6.3 ± 0.1^{g}	41.9 ± 0.3^{a}
Commercially parboiled sample		83.6 ± 0.1	87.9 ± 0.3	92.5 ± 0.2	0.4 ± 0.3	96.3 ± 0.4

[A]Means ± standard deviations from 2 replicates within a column having the same letter(s) are not significantly different at 5% level based on Tukey's honestly significant differences test.

Lamberts and others 2006; Manful and others 2008). Table 5 and Figure 2 show the thermal properties of the head rice flours as affected by cultivar, parboiling condition, and cultivar–parboiling interaction. Gelatinization temperature parameters (onset, peak, and conclusion) generally shifted to higher values, whereas gelatinization enthalpy decreased as a result of parboiling. Onset gelatinization temperature ranged 71 to 75.8 °C and 72.8 to 81.6 °C for the nonparboiled and parboiled head rice samples, respectively. On the other hand, gelatinization enthalpy ranged from 9.8 to 10.6 and 5.8 to 8.8 J/g for the nonparboiled and parboiled samples, respectively. The results are in agreement with previous studies that gelatinization temperature increased, whereas gelatinization enthalpy decreased with the severity of parboiling treatment (Biliaderis and others 1993; Ong and Blanshard 1995; Islam and others 2002; Lamberts and others 2006; Manful and others 2008). The increased onset gelatinization temperature in parboiled rice may be attributed to annealing effect as a result of soaking (Knutson 1990; Nakazawa and Wang 2003).

Specific variations in thermal properties due to cultivar, feedstock, and parboiling condition were also noted. For Cheniere and Wells, differences in onset and peak gelatinization temperature between RR and BR, and between mild and severe parboiling were more pronounced. The values were higher for BR and severe parboiling, respectively. These trends were not observed with Bolivar and Dixiebelle; RR and BR parboiled under mild conditions showed similar onset and peak temperature and so were the BR and RR parboiled under severe conditions.

The amount of gelatinized starch in the parboiled head rice samples based on DSC measurements of gelatinization enthalpy ranged 13.2% to 41.9%. The values are much lower compared with that of the commercially parboiled sample used as reference (96.3%). The amount of gelatinized starch is an indicator of the severity of parboiling process and research in the past also correlated this parameter with head rice yield. It was reported that maximum head rice yield can be achieved when endosperm starch is about 40% gelatinization, and that excessive parboiling is not necessary to obtain maximum head rice yields (Marshall and others 1993). Similarly,

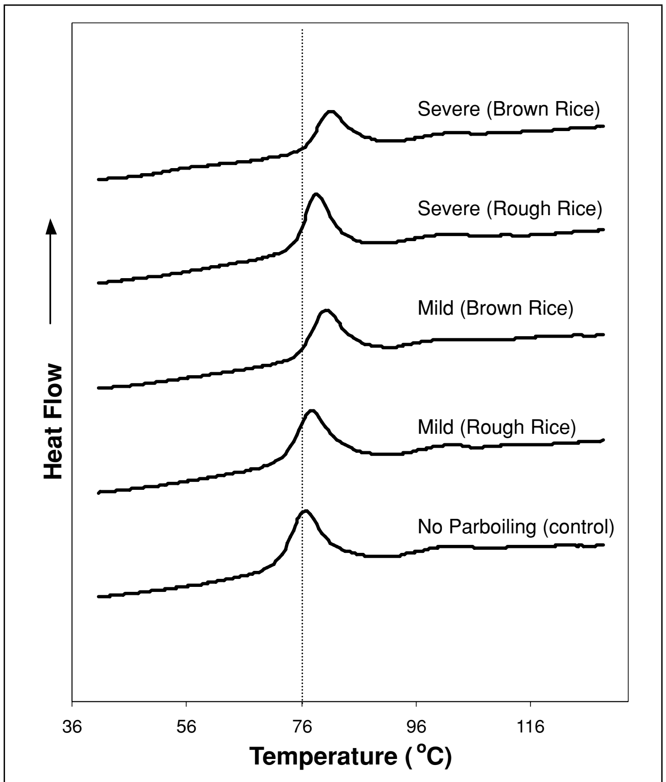

Figure 2—Differential scanning calorimeter traces of Wells flour thermal properties as affected by laboratory-scale parboiling treatments.

the head rice yields of the samples parboiled under severe conditions (80.1% to 89.6%) were comparable to the reference sample (87.6%) (Table 1), despite the lower percentage of gelatinized starch in the laboratory parboiled samples (30.7% to 41.9% compared with 96.3%). The amount of gelatinized starch varied among cultivars possibly due to differences in starch properties and grain thickness (Biswas and Juliano 1988).

Table 6 — Cooking and textural properties of rice as affected by cultivar, parboiling condition, and cultivar–parboiling interaction.[A]

Cultivar	Parboiling condition/ feedstock	Water uptake ratio	Volumetric expansion (cm^3/g)	Leached material (%)	Hardness (N)	Stickiness (N s)
Bolivar	Control (no parboiling)	2.4 ± 0.2^{ab}	6.0 ± 0.5^{a}	4.2 ± 0.4^{d}	73.7 ± 2.0^{cd}	3.6 ± 0.3^{ab}
	Mild/rough rice	2.4 ± 0.1^{ab}	5.6 ± 0.1^{bc}	3.0 ± 0.5^{gh}	75.4 ± 4.2^{bc}	3.2 ± 0.3^{abc}
	Mild/brown rice	2.1 ± 0.1^{ef}	5.4 ± 0.3^{bcd}	3.2 ± 0.3^{fg}	79.3 ± 3.8^{ab}	3.1 ± 0.5^{abc}
	Severe/rough rice	1.6 ± 0.1^{j}	5.0 ± 0.4^{def}	3.0 ± 0.1^{gh}	80.8 ± 4.2^{a}	2.7 ± 0.7^{cde}
	Severe/brown rice	1.7 ± 0.2^{ij}	4.9 ± 0.5^{ef}	2.5 ± 0.1^{h}	81.8 ± 1.9^{a}	2.6 ± 0.3^{cde}
Cheniere	Control (no parboiling)	2.3 ± 0.1^{bcd}	5.2 ± 0.2^{cdef}	6.9 ± 0.4^{a}	60.9 ± 3.4^{i}	3.7 ± 0.4^{a}
	Mild/rough rice	2.1 ± 0.1^{ef}	5.3 ± 0.2^{cde}	7.4 ± 0.4^{a}	64.7 ± 4.0^{fghi}	3.6 ± 0.4^{ab}
	Mild/brown rice	2.3 ± 0.1^{de}	5.1 ± 0.2^{def}	7.2 ± 0.7^{a}	66.2 ± 1.1^{efgh}	3.6 ± 0.3^{ab}
	Severe/rough rice	1.8 ± 0.2^{hi}	4.3 ± 0.3^{h}	5.0 ± 0.1^{c}	67.6 ± 3.8^{efg}	3.2 ± 0.2^{abc}
	Severe/brown rice	1.7 ± 0.1^{ij}	4.4 ± 0.2^{gh}	5.5 ± 0.5^{bc}	67.8 ± 1.4^{ef}	3.1 ± 0.2^{abc}
Dixiebelle	Control (no parboiling)	2.4 ± 0.1^{ab}	5.8 ± 0.4^{ab}	3.9 ± 0.1^{de}	63.2 ± 1.9^{ghi}	2.9 ± 0.6^{bcd}
	Mild/rough rice	2.4 ± 0.2^{ab}	5.2 ± 0.1^{cdef}	3.8 ± 0.2^{def}	62.9 ± 1.6^{hi}	2.8 ± 0.4^{bcd}
	Mild/brown rice	2.2 ± 0.1^{de}	5.2 ± 0.2^{cdef}	3.5 ± 0.7^{efg}	63.6 ± 2.9^{fghi}	2.1 ± 0.3^{def}
	Severe/rough rice	2.0 ± 0.1^{fg}	4.3 ± 0.3^{h}	3.0 ± 0.1^{gh}	74.9 ± 3.4^{bcd}	2.0 ± 0.3^{ef}
	Severe/brown rice	1.9 ± 0.1^{gh}	4.4 ± 0.3^{gh}	2.4 ± 0.1^{h}	81.1 ± 1.6^{a}	1.9 ± 0.2^{f}
Wells	Control (no parboiling)	2.5 ± 0.1^{a}	5.2 ± 0.1^{cdef}	5.8 ± 0.2^{b}	61.6 ± 2.0^{i}	3.7 ± 0.1^{a}
	Mild/rough rice	2.3 ± 0.3^{bcd}	5.1 ± 0.3^{def}	5.0 ± 0.1^{c}	62.0 ± 1.5^{hi}	3.2 ± 0.5^{abc}
	Mild/brown rice	2.4 ± 0.2^{ab}	5.3 ± 0.1^{cde}	4.9 ± 0.3^{c}	67.8 ± 2.4^{ef}	3.6 ± 0.3^{ab}
	Severe/rough rice	2.0 ± 0.2^{fg}	5.1 ± 0.2^{def}	5.0 ± 0.2^{c}	67.8 ± 1.7^{ef}	3.2 ± 0.7^{abc}
	Severe/brown rice	2.1 ± 0.1^{ef}	4.8 ± 0.2^{fg}	4.8 ± 0.1^{c}	70.7 ± 3.3^{de}	3.2 ± 0.4^{abc}
Commercially parboiled sample		1.8 ± 0.2	3.9 ± 0.3	2.7 ± 0.4	79.5 ± 1.9	2.2 ± 0.1

[A]Means ± standard deviations from 2 replicates within a column having the same letter(s) are not significantly different at 5% level based on Tukey's honestly significant differences test.

Cooking quality and cooked rice texture

As shown in Table 6, water uptake ratio, volumetric expansion, and the amount of leached materials during cooking generally decreased as a result of parboiling. The decrease was dependent on cultivar, parboiling condition, and cultivar–parboiling interaction (Table 2). The leached materials consisted of 89.4% to 95.9% starch, 1.2% to 7.4% crude protein, 0.2% to 0.9% crude fat, and 0.2% to 0.7% simple sugars. Cheniere was unusually higher in leached materials compared with the other 3 cultivars (5% to 7.4% for Cheniere and 2.4% to 5.8% for the other 3) as previously reported (Patindol and others 2007). Bolivar and Dixiebelle parboiled under severe conditions (both BR and RR) were similar to the reference sample in cooking characteristics. Cooked rice hardness generally increased (60.9 to 73.7 compared with 62 to 81.8 N, for nonparboiled and parboiled samples, respectively); whereas, cooked rice stickiness decreased (2.9 to 3.7 compared with 1.9 to 3.6 N s, for nonparboiled and parboiled samples, respectively) as a result of parboiling, and these trends are in agreement with previous studies (Rao and Juliano 1970; Kato and others 1983; Ali and Bhattacharya 1980; Biswas and Juliano 1988; Ong and Blanshard 1995; Islam and others 2001). The change in cooked rice texture (hardness and stickiness) was more evident in the severely parboiled samples (both BR and RR). The increase in cooked rice hardness subsequent to parboiling has been mainly attributed to the reassociation of gelatinized starch (Ali and Bhattacharya 1980; Biswas and Juliano 1988; Ong and Blanshard 1995). In addition, Derycke and others (2005) inferred that a protein barrier (composed of proteins linked through disulfide bonds) may form during parboiling and this may also limit the leaching of solids during cooking, increase hardness, and decrease the stickiness of cooked rice. With respect to cultivar differences, the pasting, cooking and textural properties of Cheniere were different from those of the other 2 high-amylose cultivars (Bolivar and Dixiebelle), and these trends were also reported in a previous study (Patindol and others 2007). The greater amount of leached materials, lower volumetric expansion, lower paste viscosity, and lower cooked rice hardness of Cheniere were associated with lower weight-average molar mass, shorter average chain length, lower proportion of long chains and higher proportion of short chains in its amylopectin (Patindol and others 2007). The structural features of Cheniere amylopectin were similar to those of Wells (Patindol and others 2007); present data also show that these 2 cultivars behave similarly when subjected to parboiling.

Conclusions

Head rice yields improved when RR and BR were subjected to severe parboiling, but decreased under mild parboiling. Parboiling generally resulted in decreased head rice whiteness, decreased apparent amylose, and increased total lipids. Changes in pasting and thermal properties were more pronounced for severe parboiling and for parboiling carried out with BR as the feedstock rather than RR. Despite their differences in pasting and thermal properties, the cooking characteristics (water uptake ratio, leached materials, and volumetric expansion) and cooked rice texture (hardness and stickiness) of severely parboiled RR and BR were comparable. BR was shown to be a comparable feedstock to RR for parboiling. The laboratory-scale parboiling procedure provides a mean to optimize parboiling conditions (particularly time, pressure, and temperature in steaming) for a specific cultivar to efficiently achieve the desirable properties of the resulting product.

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