Functional and Digestive Characteristics of Extruded Rice Flour

Rolfe J. Bryant,[1,2] Ranjit S. Kadan,[3] Elaine T. Champagne,[3] Bryan T. Vinyard,[4] and Debbie Boykin[5]

ABSTRACT

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Waxy (short grain), long grain, and parboiled (long grain) rice flours were extruded using three different temperatures and five different water feed rates. The water absorption and water solubility index of the extrudates was 0.67–5.86 and 86.45–10.03%, respectively. The fat absorption index was similar to that of unextruded flours with an average value of 0.96 g/g ± 0.12. Bulk density decreased with an increase in moisture, except waxy rice, which had a quadratic relationship. The viscosity profiles for long grain and parboiled rice were similar. Both initially increased in viscosity (>130 RVU), then decreased to ≈40 RVU. The final viscosity was ≈60 RVU. Waxy rice viscosity remained low (<20 RVU), then doubled upon cooling. The main difference in the digestion profiles was due to temperature. The flours extruded at 100°C digested significantly slower than those extruded at 125 and 150°C. Significant differences were not detected for a given temperature and moisture ($P > 0.05$) except for long grain and parboiled rice extruded at 100°C and 15% added moisture ($F = 4.48$, $P = 0.03$) and 150°C and 20% added moisture ($F = 3.72$, $P = 0.05$). Moisture appeared to have little effect for a given temperature, except when parboiled rice was extruded at 150°C. The digestion rate for 11 and 25% added moisture was significantly less than that for 20% ($P \leq 0.05$).

World rice production is projected at a record 400 million metric tons (milled basis) in 1999/2000, with the United States producing 6.6 million metric tons. Although the cost of rice is higher per pound than that of corn and wheat, its application in value-added products could give the industry new avenues of use, thus increasing its demand.

Some unique functional properties of rice such as flavor carrying capability, hypoallergenicity, and bland flavor make it a desirable grain to be used in value-added products. Some examples of these products include gluten-free rice bread (Deis 1997), tortillas, beverages, processed meats, and low-fat sauces, puddings, or salad dressings (McCue 1997). Modifying the rice flour can change its functional properties in such a way that it may also be used as a substitute in other value-added products.

Rice has also elicited different glycemic responses in healthy individuals (Wolever et al 1990). This has been attributed to factors, such as cultivar, amylose content, processing, and cooking time (Snow and O'dea 1981; Goddard et al 1984). These factors seem to increase or decrease the accessibility of the starch to digestive enzymes. However, a correlation between rice cultivar or amylose content and digestion is not as well defined as that of processing or cooking time (Panlasigui et al 1991).

Extrusion cooking, because of its low cost and continuous processing capability, is one processing method that has been used to modify the functional and digestible characteristic of cereal grains. Although it has been extensively used to produce such products as cereals, snacks, bread substitutes, precooked flours, animal feeds, and dietetic foods (Camire 1990), only in recent years has it been used for rice products (Pan et al 1992). This high temperature and short time (HTST) processing is capable of thoroughly gelatinizing the starch even at low moisture levels (Gomez and Aguilera 1983). Although extrusion does not change the starch content or degrade the starch moiety to low molecular weight sugars, it does cause macromolecular degradation (Colonna et al 1989). This causes the starch to have cold pasting ability and different digestibility profiles without increasing Maillard reactions. Bjorck and others (Mercier and Feillet 1975; Asp and Bjorck 1984; Bjorck et al 1984) have shown that the digestibility of extruded starch is directly related to the severity of the extrusion process. Also, the short residence time that is associated with high screw speed can form amylose-lipid complexes, starch-protein complex, or resistant starch which may decrease digestion (Mercier 1980; Eerlingen et al 1994). Extruded rice can also be easily fortified, and broken or immature kernels can be used.

Many extruded cereal grains such as wheat, corn, millet, and rye have been tested for digestibility (Mercier and Feillet 1975; Mercier 1980; Asp and Bjorck 1984; Bjorck et al 1984; Dahlin and Lorenz 1993; Eerlingen et al 1994). Also, there have been studies on the digestibility of cooked and extruded rice (Panlasigui et al 1991, 1992; Casiraghi et al 1993; Zhang et al 1996). Most investigators use enzymatic assays to determine the digestibility of starchy products. Although in vitro methods are not as complex as in vivo systems, they correlate very well (Holm et al 1985; Lee et al 1985). In vitro systems are also less expensive and time-consuming. However, there is little information on the effect of temperature, moisture, and amylose content on the functionality and digestibility of extruded rice. Therefore, the objective of this research was to examine the effect extrusion temperature and moisture (water feed rate) had on the functional and digestive properties of selected rice flours.

MATERIALS AND METHODS

A 3×3×5 factorial randomized complete block design experiment was conducted using rice flour. Each sample was examined for bulk density, water absorption index, water solubility index, fat absorption, viscosity profile, and digestion profile (Table I).

Waxy (short grain), long grain (Cypress), and parboiled (long grain) rice were obtained commercially. The rice samples were ground in a Kolloplex sieveless impact stud mill (Alpine, Augsburg, Germany) to a powder (<100 mesh, <149 µm) and stored at 20°C and 50% rh. The rice flours were analyzed for moisture, protein, lipid, and amylose contents (Kadan et al 1997). Moisture was determined by oven drying according to AOAC method 925.10 (AOAC 1997). Protein contents (N × 5.95) were determined by the combustion method using a nitrogen analyzer (model FP-428, Leco, St. Joseph, MI). Lipids were extracted with 100 mL of petroleum ether from 5 g of ground rice flour using a

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[1] USDA, ARS, Dale Bumpers National Rice Research Center, P.O. Box 287, Stuttgart, AR 72160. Names are necessary to report factually on available data; however, the USDA neither guarantees nor warrants the standard of the product, and the use of the name by the USDA implies no approval of the product to the exclusion of others that may also be suitable.

[2] Corresponding author. Phone: 870-672-9300 (Ext. 227), Fax: 870-673-7581, E-mail address: rbryant@spa.ars.usda.gov

[3] USDA, ARS, Southern Regional Research Center, 1100 Robert E. Lee Blvd., New Orleans, LA 70124.

[4] USDA, REE, ARS, Beltsville Area, Office of the Director, Bldg, 001, BARC-WEST RM 010, 10300 Baltimore Blvd., Beltsville, MD 20705.

[5] USDA, ARS, Mid South Area Office, P.O. Box 225, Stoneville, MS 38776.

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Soxhlet extraction apparatus for 6 hr (AACC 2000). Amylose was determined by the simplified assay method developed by Juliano (1971).

A self-cleaning corotating twin-screw extruder with a square 7-mm die (model ZSK-30, Werner-Pflelderer, Ramsey, NJ) was used. The screws were 975 mm long with the following configuration from feed to die: (number of elements-screw flight pitch/length in mm) 1-spacer/10, 2-42/42, 1-42/21, 2-42/42, 5-28/28, 5-kneading block with 45° offset/20, 2-28/28, 5-kneading block with 45° offset/20, 4-28/28, 5-kneading block with 90° offset/28, 20-20/20, and 2-spacer/1. Zones 1 and 2 were set at 60°C, whereas, zones 3 through 5 were set at 100, 125, or 150°C. The extrudate temperature was taken with a thermocouple located behind the die and was within 5°C of zone 5. The screw speed was set at 180 rpm with a feed rate of 100 g/min. Moisture of the flour was increased by adding 11, 15, 20, 25, and 30 mL of water/100 g of flour through a water port located in zone 1. Moisture content was measured after the extrudate cooled (<20 min) to room temperature (25°C) and after grinding. The extrudates were ground in a mill containing a 1/4-in. sieve (Reeves Pulley Co., Columbus, IN) and then in the sieveless impact stud mill to a powder (<100 mesh). The powder was stored in zip-lock bags at room temperature until other analyses were done. If needed, the extrudates were dried overnight in an oven at 40°C before grinding.

TABLE I
Treatment and Responses

Treatment			
Rice Type	**Temp. (°C)**	**Flow Rate (%)**	**Responses**
Waxy	100	11	Bulk density
Long grain	125	15	Water absorption index
Parboiled	150	20	Water solubility index
		25	Fat absorption
		30	Viscosity profile
			Digestion profile

TABLE II
Proximate Analysis of Unextruded Rice Flours (%)[a]

Rice Flour	Amylose	Moisture	Protein	Lipid
Waxy	0.3	10.8	6.9	0.6
Long grain	20.1	12.4	8.1	0.4
Parboiled	21.0	11.9	8.6	0.5

[a] Calculated on as-is basis.

TABLE III
Calculated Moisture of Rice Flour During Extrusion Cooking (%)

	Flour Moisture Flow Rate (%)				
Rice Flours	**11**	**15**	**20**	**25**	**30**
Waxy	19.6	22.4	25.7	28.6	31.4
Long grain	21.1	23.8	27.0	29.9	32.6
Parboiled	20.6	23.4	26.6	29.5	32.2

Water absorption index (WAI) and water solubility index (WSI) were determined using the method of Anderson et al (1969). Each sample (2.5 g) was suspended in 30 mL of distilled water (30°C) in a 50-mL preweighed centrifuge tube by vortexing. The tubes were placed in a 30°C water bath and intermittently stirred for 30 min. The suspension was centrifuged for 10 min at 3,000 × *g* and the supernatant was decanted into a preweighed 50-mL beaker. The weight of the precipitate was used to calculate the WAI which was reported as a ratio (wt gain/wt of sample, dwb). The supernatant from the WAI was dried at 95°C and the weight of dried solids were used to determine the WSI (%).

Fat absorption index (FAI) characteristics were determined using a method by Lin and Humbert (1974). Dewaxed rice oil (3 mL) (Riceland Food Inc., Stuttgart, AR) was added to 0.5 g of each sample in a 15-mL conical graduated centrifuge tube. After stirring with a solid glass rod, each sample was vortexed and allowed to stand at room temperature (25°C) for 30 min. The contents were centrifuged at 1,650 × *g* for 25 min and the volume of free oil read (FAI was expressed as g of oil absorbed/g of flour).

Bulk densities were determined using a modification of the method by Wollermann and Makstell (1958). Each sample (10.00 g) was weighed into a 25-mL graduated cylinder. The cylinder was tapped on the bench top until no more settling was observed. A reading was taken both before and after packing. Bulk density was expressed as grams per cubic centimeter.

Viscosity was determined using a Rapid Visco Analyser (RVA) Model 3CR (Newport Scientific, Eden Prairie, MN), Thermocline for Windows software (ver.1) and Approved Method 61-02 (AACC 2000). Sample (3 g based on 12% moisture) were added to 25 mL of water. The sample was heated to 50°C for 1 min and then ramped to 95°C at a rate of 11.84°C/min. After holding at 95°C for 2.5 min, the temperature was decreased to 50°C at the

TABLE IV
Moisture Content (%) of Extruded Rice Flours Before and After Grinding for Each Treatment on Day 1 (A) and Day 2 (B)[a–c]

% Added	100°C (A)		100°C (B)		125°C (A)		125°C (B)		150°C (A)		150°C (B)	
Moisture	**Before**	**After**	**Before**	**After**	**Before**	**After**	**Before**	**After**	**Before**	**After**	**Before**	**After**
Waxy												
11	12.3	10.2	11.5	13.1	12.4	10.2	12.8	11.2	10.0	9.3	10.0	10.0
15	16.3	11.1	17.1	9.0	13.8	6.4	13.9	11.1	10.5	10.4	11.3	10.8
20	20.6	12.4	22.4	11.1	14.8	6.8	15.7	8.4	10.9	10.3	12.5	11.6
25	23.3	12.7	25.9	12.9	16.5	7.1	17.1	8.5	12.3	12.7	13.7	12.8
30	25.3	na[d]	28.3	13.1	19.2	7.9	17.5	9.7	17.4	14.7	13.0	13.4
Long grain												
11	10.2	8.2	12.7	11.1	13.1	10.9	9.9	9.3	10.3	7.8	10.5	8.6
15	17.4	6.4	17.1	6.9	15.1	4.8	13.4	12.0	10.8	9.0	11.2	9.8
20	21.7	9.2	22.8	11.7	17.8	5.1	16.9	5.6	11.1	10.4	12.7	11.0
25	25.8	12.1	26.7	12.1	21.4	5.5	18.5	6.7	11.3	11.0	13.6	11.7
30	27.7	11.9	28.3	10.3	25.2	6.9	21.6	7.5	14.4	12.5	16.1	13.5
Parboiled												
11	15.9	9.8	11.1	11.7	13.6	10.0	12.4	11.5	8.7	8.2	9.3	9.7
15	20.6	7.8	20.3	10.2	16.0	5.9	16.0	13.4	9.8	8.7	11.3	11.1
20	24.5	11.2	23.8	11.1	21.4	4.9	17.2	8.4	10.8	9.5	13.7	12.6
25	25.5	12.0	27.3	9.2	na	6.3	18.6	9.7	12.2	10.6	12.9	14.5
30	28.1	11.3	30.4	10.8	27.4	7.6	20.4	8.6	19.0	13.2	15.6	15.1

[a] R^2 of triplicate moisture values pooled across all treatments 0.391 and 0.472 for before and after measurements, respectively.
[b] Calculated on as-is basis.
[c] Before = extrudate after cooling; after = extrudate after grinding.
[d] Not available.

same rate and held for 1.4 min. The sample was constantly stirred and the total run time was 12.5 min. Each sample was also run using a 5-g sample. Viscosity was measured in RVA units (RVU). One RVU is equal to ≈12 cP. Cold paste viscosity was evaluated by adding 5 g of sample, based on 12% moisture, to 25 mL of water. The mixture was run on the RVA at a constant temperature (25°C) for 10 min while stirring. The maximum RVU achieved was taken as the cold pasting viscosity.

In Vitro Digestion

α-Amylase (EC 3.2.1.1) type IX-A from human saliva (Sigma, St. Louis, MO) was reconstituted using a buffer containing 20 m*M* sodium phosphate (pH 6.9) and 6.7 m*M* sodium chloride. A stock solution of reconstituted enzyme (25 units/mL) was stored at 4°C until use. The stock solution was diluted to 5 units/mL using the described buffer before each test. One unit is defined as the amount of enzyme needed to liberate 1.0 mg of maltose from starch in 3 min at pH 6.9 and 20°C.

Digestion was performed using neocuproine hydrochloride (2,9-demethyl-1,10-phenanthroline • HCl) and cupric sulfate as a reducing agent (Dygert et al 1965). Samples (1 g each, dry matter) were weighed in duplicate into 50-mL screw-cap glass tubes and 15 mL of 20 m*M* sodium phosphate buffer (pH 6.9) was added. After prewarming for 30 min at 37°C, starch hydrolysis was achieved by adding 5 units of prewarmed enzyme (37°C) to one duplicate of each sample. Distilled water (1 mL) was added to the other duplicate which was used as a blank. Each tube was vortexed and incubated at 37°C for 2 hr. Every 30 min, 1 mL of sample was removed from each tube after vortexing and diluted to 10 mL with distilled water. The diluted samples were then placed in boiling water for 20 min to stop the reaction. Unextruded samples (1 g) were placed in screw-cap tubes containing 15 mL of buffer, cooked for 30 min in boiling water, cooled and assayed with the same enzyme system.

After cooling to room temperature (25°C), each sample was further diluted fivefold and 0.5 mL was placed in a 25-mL screw-cap glass tube with 5 mL of solution A (40 g of anhydrous Na_2CO_3, 16 g of glycine, 0.450 g of $CuSO_4 \bullet 5H_2O$/L of distilled water) and 5 mL of solution B (0.12 g of neocuproine • HCl/100 mL of distilled water). The tubes were placed in boiling water for 12 min and, after cooling in cold water to room temperature, the optical density was determined at 450 nm against a reagent blank (0.5 mL of distilled water instead of sample). If a precipitate formed during heating, the samples were diluted and the color development assay repeated.

The amount of starch digestion was determined by comparing the absorbance of each sample to a standard maltose calibration curve, which was established each day, and reporting the results as maltose equivalents. The amount of maltose equivalence for each sample without enzyme was subtracted from the sample with enzyme. To compare runs made on different days, one modified rice flour was chosen as a control and analyzed with each run. An average absorbance was obtained for each 30-min period for that control and each run was then normalized to the control.

Statistical Analysis

Each combination of rice flour, temperature, and flow rate treatment was prepared separately. This treatment structure is a 3×3×5 factorial with each replicate being performed on a separate day yielding a randomized complete block design. Averages of duplicate readings recorded for each measurement taken on a given day were used in the statistical analyses. Analysis of variance (ANOVA) for the three-way model examining rice flours, temperatures, and flow rates were conducted (SAS Institute, Cary, NC). Least significant difference (LSD) values for subsequent comparison of means were calculated using the fixed effect ANOVA template in PASS (Number Cruncher Statistical

TABLE VI
Comparisons of Digestion Profiles of Unextruded Rice Flours[a]

Comparasions	*F*-Test	Pr > *F*
UW vs W	4.69	0.03
UL vs L	1.00	0.10
UP vs P	0.39	0.53
W vs L	0.63	0.43
W vs P	0.79	0.38
L vs P	2.81	0.95
UW vs UL	0.14	0.71
UW vs UP	13.46	<0.01
UL vs UP	10.88	<0.01

[a] Uncooked waxy (UW), uncooked long grain (UL), uncooked parboiled (UP), cooked waxy (W), cooked long grain (L), and cooked parboiled (P).

TABLE V
Bulk Density, Water-Absorption Index (WAI), and Water-Solubility Index (WSI) of Extruded Rice Flours[a–c]

%Added	100°C			125°C			150°C		
Moisture	Density	WAI	WSI	Density	WAI	WSI	Density	WAI	WSI
Waxy[d]									
11	0.82	1.35	48.04	0.90	0.79	72.47	0.89	0.63	86.45
15	0.86	1.24	57.06	0.90	0.79	73.94	0.87	0.80	80.66
20	0.89	1.45	56.69	0.92	0.84	73.49	0.87	0.97	74.13
25	0.89	2.04	46.36	0.91	0.82	75.28	0.87	1.22	69.37
30	0.72	2.54	39.27	0.93	0.98	70.88	0.80	1.47	55.28
Long grain[e]									
11	0.89	4.42	34.40	0.85	3.08	50.14	0.80	2.80	46.36
15	0.93	4.48	37.86	0.89	2.83	51.48	0.79	3.00	54.40
20	0.87	5.17	17.26	0.92	3.04	55.98	0.77	3.33	40.43
25	0.79	4.56	10.03	0.93	4.22	45.75	0.76	3.83	35.33
30	0.77	4.27	12.82	0.92	4.72	38.72	0.77	4.45	24.98
Parboiled[f]									
11	0.84	4.81	34.22	0.86	2.68	57.67	0.86	3.03	58.54
15	0.87	5.86	31.04	0.81	3.93	49.57	0.79	3.66	57.05
20	0.74	5.57	17.72	0.83	2.70	64.97	0.85	3.96	47.76
25	0.67	4.78	17.14	0.91	4.43	48.30	0.80	4.09	34.37
30	0.70	4.79	12.92	0.90	4.54	34.83	0.75	4.82	30.10

[a] Means of duplicate analyses
[b] Root MSE values of duplicate density, WAI, and WSI values pooled across all treatments were 0.056, 0.618, and 8.543, respectively.
[c] LSD (α = 0.05; 1-β = 0.70) for bulk density, WAI, and WSI were 0.15, 1.54, and 21.22, respectively.
[d] WAI and WSI for unextruded waxy rice flour were 2.35 and 3.49, respectively.
[e] WAI and WSI for unextruded long grain rice flour were 2.25 and 1.22, respectively.
[f] WAI and WSI for unextruded parboiled rice flour were 4.06 and 2.81, respectively.

Systems, Kaysville, UT). The regression procedure in SAS was used to fit models appropriate for describing trends across flow rate for each rice flour and temperature combination.

Digestion profile is the relationship of absorbance as a function of digestion time. Therefore, analysis of covariance (ANOCVA) was used to examine the effects of flour type, temperature, and flow rate on the digestion profile. These analyses were conducted using the GLM procedure in SAS.

RESULTS AND DISCUSSION

The proximate analysis and amylose content of the samples are shown in Table II. The amylose contents for long grain and parboiled rice were 20.1 and 21.0%, respectively. The waxy rice was virtually 100% amylopectin. Amylose, moisture content, and temperature are considered the most important characteristics for controlling the functionality of extruded rice (Colonna et al 1989; Pan et al 1992). The moisture of the flours during extrusion could not be measured directly, therefore they were determined mathematically (Table III) using the formula: calculated moisture (%) = [(A + B)/(C + B)] (100) where A = flour moisture flow rate (g/min), B = water flow rate (g/min), C = flour flow rate (g/min).

Table IV shows the moisture of the extrudate before and after grinding. The moisture of the unground extrudate range was 8.7–30.4%. The main difference in moisture is attributed to the fact that the extrudates produced at higher temperatures lost more moisture during cooling than those extruded at lower temperature. However, parboiled extrudate generally had a lower final moisture than waxy or long grain samples. The moisture of the ground extrudates was used to calculate the dry weight basis of each sample.

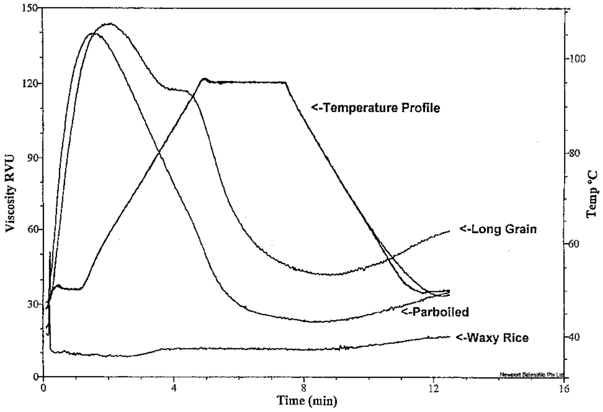

Fig. 1. Typical RVA profiles of modified flours using 5 g/25 mL of water.

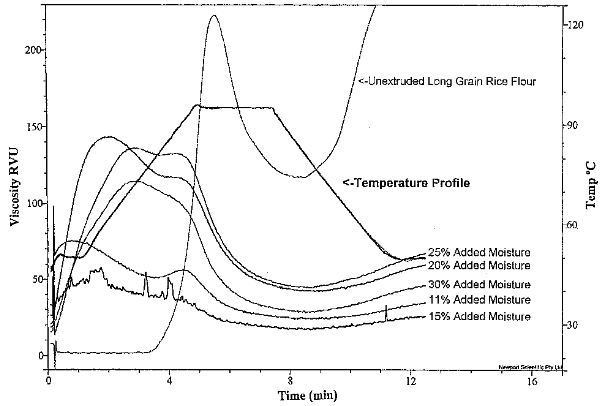

Fig. 2. RVA profiles for unextruded long grain rice flour and modified flour of long grain extruded at 100°C and different water feed rates with the temperature profile overlayed.

Bulk density can be used to determine feed rates and transportation cost. Pan and coworkers (1992) compared processing parameters and ingredients formulations on the effect of properties of extruded expanded rice products and found that moisture was the most important factor affecting bulk density. The bulk density averages are shown in Table V. The ANOVA indicated signficant main-effects for rice, temperature, and flow rate as well as a significant temperature by flow rate interaction and a significant rice by temperature interaction ($\alpha = 0.05$ and $1-\beta = 0.70$). The bulk density of the flours extruded at 100 and 150°C decreased with increase in moisture. Whereas, the bulk density of the flours extruded at 125°C increased with increase in moisture. Although most of the temperatures fit the log-linear model, the waxy rice flour extruded at 100°C had a quadratic relationship. At 100°C and 20–30% added moisture, most of the extrudates became very hard after cooling and at that temperature and moisture the extrudate of waxy rice was very sticky and collapsed. Those conditions made the extrudates hard to grind.

The extrusion conditions had little effect on fat adsorption. The FAI of the extruded flours were similar to that of the unextruded rice flours. The average value was 0.96 g/g ± 0.12 with a range of 0.8–1.2 g/g. Abdel-Aal and coworkers (1992) also observed that extrusion conditions had little effect on FAI when rice flour and fababean protein concentrate blend was used. The FAI range for products was 2.4–3.0 g/g.

WAI can be used to give an indication of cold paste viscosity, which correlates with the degree of cook, and WSI can be used as an indication of the degree of molecular damage (Paton and Spratt 1981; Colonna et al 1989). The data for WAI and WSI are shown in Table V. For each rice flour and temperature, the WAI and WSI trends with respect to flow rates were described by fitting a quadratic, log-linear, or mean regression model. The R^2 range for these regression models was 0.39–0.95. The ANOVA indicated significant main effects for rice, temperature, and flow rate as well as a significant temperature by flow rate interaction ($\alpha = 0.05$). Any pairwise comparison among flour, temperature, and flow rate means can be made visually using LSD values reported in Table V.

The WAI increased with increase in added moisture and fit the log-linear model, except for the extruded flours of long grain and parboiled rice at 100°C which had a concave quadratic relationship. The WAI for the extruded flours from waxy rice was lowest at 0.63 for the flour extruded at 150°C and 11% added moisture to 2.54 for the flour extruded at 100°C and 30% added moisture. The WAI of the extruded flours of long grain and parboiled rice were similar with the highest WAI, 5.17 and 5.86, occurring in the flours extruded at 100°C and 15–20% added moisture, respectively.

The WSI decreased with increase in added moisture except for the extruded flours of long grain and parboiled rice at 125°C and waxy rice at 100°C which had a concave quadratic relationship. The extruded flours of waxy rice had the highest WSI range at

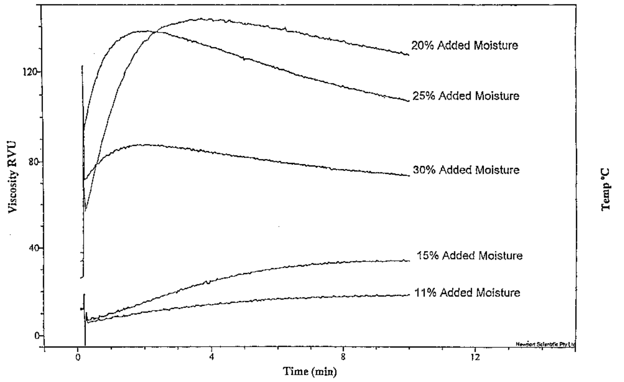

Fig. 3. RVA profiles obtained at 25°C for 10 min for long grain rice flour extruded at 100°C and water feed rates.

39.27 for the flour extruded at 100°C and 30% added moisture to 86.45 for the flour extruded at 150°C and 11% added moisture. The WSI for long grain and parboiled rice were similar with the highest occurring in the flour extruded at 125°C and 20% added moisture. The lowest WSI was observed in the extruded flours of long grain and parboiled rice extruded at 100°C and high moisture content, 25–30% added moisture.

Earlier reports have shown that an increase in moisture decreased the WSI but had little effect on WAI and FAI and that higher barrel temperature also decreased WSI (Anderson et al 1969; Abdel-Aal et al 1992). Although our results on WSI and FAI are in agreement, the results on WAI showed an increase with increased moisture and decreased temperature. Some investigators also have reported finding little change in WAI for high amylose starches even with temperatures up to 200°C (Colonna et al 1989) whereas, the extruded waxy rice flours (0.3% amylose) we examined had much lower WAI than the extruded long grain and parboiled rice flours (20.1 and 21.0% amylose, respectively) extruded at the same temperature and water feed rate. Also, our results agreed with the literature which states that the WSI of waxy rice was higher than that of nonwaxy rice extruded at the same moisture content and operating conditions (Pan et al 1992). A flour with high WSI and low WAI, such as waxy rice extruded at 150°C and 11% added moisture, would be ideal for use in a sport drink because of the high solubility. Further, a flour with high WAI and low WSI could be used in a product such as a low fat soup where the main concern is a high viscosity. The viscosity of such a product can be obtained by using the water absorbing ability (WAI) of the extruded flours.

Figure 1 shows typical RVA profiles of each extruded flour at 5 g of sample/25 mL of water. The RVA profile using 3 g (9.4% solids) showed <20 RVU and rendered almost a straight line. When the sample size was increased to 5 g (16.7% solids), the RVU increased such that the individual differences became evident. At 100°C, extruded waxy rice flour had a low initial viscosity (<20 RVU) which changed little during heating. During cooling the viscosity increased slightly. The viscosity of extruded long grain flour at 100°C increased to >130 RVU during initial heating then dropped to ≈40 RVU and during cooling increased to ≈60 RVU. The viscosity profile of extruded parboiled flour was similar to that of long grain.

When the graphs are overlaid, the RVA can give a visual picture as to the degree of cook and the degree of molecular damage which correlates well with WAI and WSI, respectively (Whalen et al 1997). Figure 2 shows overlays of the RVA of the extruded flours of long grain rice which were extruded at 100°C and the RVA of unextruded long grain rice flours. A progressive transformation from raw to fully cooked to product degradation can be observed. The pattern in Fig. 2 shows a shift in the peak of the unextruded flour (raw peak) to the left (increase in cold viscosity) to a decrease in viscosity of the new peak (increase in degradation). Although most of the samples followed the pattern expected where increased moisture decreased the degree of cook, long grain rice extruded at 100°C showed a unique pattern at 20% added moisture. It produced a high viscosity (high WAI), which indicates a high degree of cold pasting ability with little or no molecular damage (low WSI). This was also confirmed when the flour was run at a constant temperature (25°C) (Fig. 3). Also, it indicates that the starch is fully cooked because the peak is shifted to the left when compared with the unextruded rice flour. The RVA profiles agrees with the WAI and WSI data and therefore can be used to screen future extruded flours for potential use in value-added products.

The starch digestion profiles of the samples were fitted to three statistical models: linear, log-linear, and log-log. The log-log model was the best fit for most of the samples ($R^2 > 0.95$), and in the case where it was not, R^2 was still ≥0.95. Therefore, the log-log model was used for further evaluation. The formula used to define the line was: absorbance = B_0 × digestion time$^{(B)}{}_1$ where B_0 is a base value. It also is an estimate of absorbance when time =1 min. B_1 explains the change in absorbance as time changes, the greater B_1 the greater the rate of digestion. B_0 and B_1 parameters were estimated by fitting a log-log trend using linear regression (Steel and Torrie 1980). The equation is shown in the exponential form.

Table VI shows the ANOCVA results for comparing digestion profile of the cooked and uncooked unextruded rice flours. As expected, there was a significant difference in digestion profile of

TABLE VIII

Parameter Estimates for Digestion Profiles of Extruded Rice Flours and Temperature[a]

Type of Flour[b]	Temperature	B_0	B_1[c]
EW	100°C	0.8022	0.854a
EL	100°C	0.7147	
EP	100°C	0.7775	
EW	125°C	0.6621	0.910b
EL	125°C	0.5731	
EP	125°C	0.5669	
EW	150°C	0.6605	0.896b
EL	150°C	0.6391	
EP	150°C	0.6219	

[a] All B_1 values were significant at $P < 0.001$.
[b] Extruded waxy (EW), extruded long grain (EL), and extruded parboiled (EP).
[c] Based on F-test for homogeniety of B_1, values not followed by the same letter differ significantly at $P < 0.05$. Absorbance = B_0 × digestion time (B_1).

TABLE VII

Parameter Estimates for Digestion Profiles for the Extruded Flours[a]

		Waxy Rice		Long Grain		Parboiled	
Temp. (°C)	Moisture (%)	B_0	B_1	B_0	B_1	B_0	B_1
100	11	0.6605	0.895	0.5456	0.924	0.8089	0.854
100	15	0.7165	0.882	0.4890	0.946	1.3973	0.721
100	20	0.7470	0.872	0.9352	0.796	0.6872	0.883
100	25	0.9730	0.813	0.6566	0.864	0.8085	0.836
100	30	0.8762	0.827	0.7384	0.842	0.8033	0.838
125	11	0.5225	0.957	0.5942	0.896	0.2714	1.069
125	15	0.7384	0.886	0.6877	0.865	0.4807	0.949
125	20	0.5925	0.934	0.6035	0.898	0.7176	0.861
125	25	0.6058	0.932	0.5414	0.930	0.9288	0.809
125	30	0.9258	0.840	0.6281	0.889	0.4926	0.937
150	11	0.5059	0.959	0.7743	0.849	0.9612	0.795
150	15	0.6132	0.915	0.6167	0.900	0.6172	0.893
150	20	0.5610	0.935	0.8234	0.833	0.3509	1.030
150	25	0.6162	0.909	0.8037	0.844	0.9716	0.794
150	30	0.6233	0.914	0.6747	0.889	0.4330	0.982

[a] All B_1 were significant at $P < 0.001$. Absorbance = B_0 × digestion time(B_1).

cooked waxy rice flour versus uncooked waxy rice flour ($P \leq 0.05$), and there was no difference in the digestion of cooked and uncooked parboiled rice flour. However, the cooked and uncooked long grain showed no difference at $P \geq 0.05$ but there was statistical differences at $P \leq 0.1$ level. The digestion profile of uncooked parboiled was statistically different from uncooked long grain and waxy rice flour ($P \leq 0.01$). There were no statistical differences in the rate of digestion between uncooked long grain and uncooked waxy rice flour ($P \geq 0.05$). Also, the digestion profiles of the three cooked flours were not statistically different from each other ($P > 0.05$).

Table VII shows the parameter estimates (B_0 and B_1) for the extruded rice flours. There were no significant differences in the digestion profile of the three rice flours for a given temperature and moisture ($P > 0.05$) with the following exceptions: long grain ($B_1 = 0.946$) and parboiled ($B_1 = 0.721$) extruded at 100°C and 15% added moisture ($F = 4.48$, $P = 0.03$); and long grain ($B_1 = 0.833$) and parboiled ($B_1 = 1.03$) extruded at 150°C and 20% added moisture ($F = 3.72$, $P = 0.05$). Other investigators (Panlasigui et al 1991; Zhang et al 1996) have studied the digestion profile of rice flours with similar amylose content and found that they were significantly different ($P \leq 0.05$). Therefore, different varieties extruded under similar conditions may have different digestion profiles than shown here. Moisture appeared to have little effect on the digestion profiles of the extruded rice flours for a given temperature, except when parboiled was extruded at 150°C. The B_1 for 11 and 25% added moisture was significantly less than the B_1 for 20% ($P \leq 0.05$). Carter et al (1998) have shown that at lower temperatures (85–105°C) there may be significant difference due to temperature and moisture.

The main difference in the digestion profiles was due to the extrusion temperature. This was best shown by combining equations with common B_1 values. The results of this are shown in Table VIII. Each extruded flour of a given temperature had the same B_1 but different B_0. The flours extruded at 100°C ($B_1 = 0.854$) were significantly different ($P \leq 0.05$) from those extruded at 125 and 150°C ($B_1 = 0.910$ and 0.896, respectively). However, there were no significant differences in the flours extruded at 125 and 150°C. Guha et al (1997) showed that the digestibility of rice flour increased as the barrel temperature increased from 80°C to 100°C then decreased.

CONCLUSIONS

Rice flour has inherent unique properties such as small starch granules that make it ideal as a fat-replacer. Modifying the flour through extrusion cooking alters its functionality, thus allowing it to be used in many other ways such as salad dressings, pasta, precooked beverage powders, or tortillas. Extrusion cooking can also increase solubility and change the viscosity profile. The changes that occur are related to the cultivar used, moisture content, and temperature conditions of the extruder.

RVA can be used to determine the degree of cook and the amount of starch degradation. It correlates well with WAI and WSI and is faster and more reproducible. The RVA profile of long grain rice flour extruded at 100°C and 20% added moisture showed that the extrudate was fully cooked with little molecular damage. This extruded flour, along with the others, is being examined for use in value-added products.

Extrusion temperature was the most significant factor affecting digestibility of extruded flour. Digestibilities of flours processed at 100°C were statistically different from those processed at 125 and 150°C. There were no significant differences among the digestion profiles of the three rice flours for a given temperature and moisture with the following exceptions: long grain and parboiled rice extruded at 100°C and 15% added moisture, and long grain and parboiled rice extruded at 150°C and 20% added moisture. Moisture appeared to have little effect on the digestion profile of the extruded rice flour for a given temperature except when parboiled rice was extruded at 150°C. The B_1 for 11 and 25% added moisture were significantly less than the B_1 for 20% added moisture indicating that digestibility was reduced at those moistures.

The statistical differences were small and therefore more studies need to be conducted in lowering the digestibility even further without damaging the starch moiety. Also, the flours need to be analyzed in vivo to see whether the digestion profile is different and to validate the glycemic response.

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