Physical and Sensory Characteristics of Extruded Products Made from Two Oat Lines with Different β-Glucan Concentrations

Ni Yao,1 Jean-Luc Jannink,2 Sajid Alavi,3 and Pamela J. White1,4

ABSTRACT

The impact of extrusion on physical and sensory properties and on the in vitro bile acid (BA) binding was examined for N979 and Jim oat (Avena sativa) lines with 8.1 and 4.8% β-glucan, respectively. Based on hardness and edibility of products made from Jim oats, moisture concentrations of 16–25% and temperatures of 165–180°C were selected for N979 extrusion. Jim-based cereal had a significantly greater (P < 0.05) expansion ratio than did N979-based cereal at most moistures. N979 cereal was browner, but not harder, than Jim cereal. Extruded products from N979 and Jim oats had 5.29–5.99% and 3.38–3.94% β-glucan, respectively. Changing extrusion temperature or moisture content did not affect β-glucan concentration in the products. N979 cereal made at 165°C and 16% moisture had greater BA binding than at other conditions, and had crispiness comparable to cereals made at other conditions. BA binding of Cheerios brand breakfast cereal was close to that of N979 cereal made at 180°C and 18% moisture, but lower than cereals made at other conditions. Cereals made from Jim and N979 oats were browner, harder, coarser, and crunchier than Cheerios breakfast cereal. Proper processing and preparation techniques should be considered when producing extruded products from high β-glucan oats.

Interest in developing foods with nutritionally functional ingredients has been driven by the market potential for foods that can improve the health and well-being of consumers. Soluble fibers from oats (Avena sativa), specifically (1,3)(1,4)-β-D-glucan (β-glucan), a cell-wall polysaccharide found in the endosperm and subaleurone layers of cereal seeds (Behall et al. 1997), reduces serum cholesterol (Anderson 1995) and lowers glucose and insulin concentrations in the plasma, thus decreasing the incidence of heart disease, obesity, cancer, and type-2 diabetes (Mäkkki and Virtanen 2001). Health benefits of oat products are well recognized (Wood et al. 2002). In 1997, the U.S. Food and Drug Administration registered oat bran, and specifically β-glucan at a level of 3 g/day, as the first cholesterol-reducing food and therefore a food that can reduce the risk of heart disease. A proposed mechanism by which oat β-glucan reduces serum cholesterol is through its ability to lower the reabsorption of bile acid (BA), thus increasing BA excretion in the feces (Drzikova et al 2005). Physical elimination of BA from the enterohepatic circulation necessitates increased synthesis of BA, which, in turn, promotes cholesterol conversion to BA in the liver (LaRusso 1983). The mechanism of interaction between β-glucan and BA is currently not fully understood. From previous research, Sayar et al. (2005) summarized the existence of three competing hypotheses. First, β-glucan may bind BA directly; second, β-glucan may inhibit the reabsorption of BA by increasing the viscosity of ileum fluids rather than any specific binding (Bowles et al. 1996; Wood et al. 2002); and third, binding may occur between β-glucan and micelles formed from bile and fatty acids rather than the isolated BA alone (Bowles et al. 1996).

Plant breeders seek to increase levels of β-glucan in oat lines that may be processed to create new, effective, nutritious, and functional foods (Cervantes-Martinez et al 2001). Increasing β-glucan content of the final product would lead to increased β-glucan intake without a concomitant increase in total carbohydrate intake. Limiting concurrent carbohydrate intake is important because studies have shown that a high-carbohydrate, low-fat diet may produce unfavorable changes in blood lipids and lipoprotein; specifically, an increase in plasma triglycerides and a decrease in high-density lipoprotein (HDL) cholesterol concentrations (Parks 2001). The health benefits associated with dietary fiber have resulted in its use in virtually all food product categories, including many products manufactured by extrusion processing where expansion results in textures that make the food appetizing and crisp (Moraru and Kokini 2003).

High-temperature short-time (HTST) extrusion cooking technology has become a popular process for preparing snack foods and ready-to-eat breakfast cereals using starch-based raw materials (Colonna et al 1989). However, the impact of processing on the function of oat-based extrusion products is not fully understood. Processing can produce substantial fragmentation of β-glucan, with subsequent effects on the physiological response. Thus, it is important to evaluate the impact of processing on β-glucan structure. Also, it is not easy to produce palatable foods with high levels of dietary fibers. Ready-to-eat breakfast cereals rich in dietary fiber are often not well expanded, exhibit a short bowl life, and most importantly from a consumer standpoint, lack crispness or crunchiness. Processing a well-expanded oat cereal by extrusion is difficult because oats have a high level of fiber, fat, and soluble gum, which leads to poor gas-holding capacity in the extruded dough and also inadequate mechanical energy input. Foods containing high β-glucan oats may especially manifest poor expansion and textural properties, thus affecting the physical and sensory properties (Meuser 2001). Standardizing extrusion parameters and evaluating the physical, chemical, and sensory properties are important in developing extruded oat products.

Evaluating the capacity of oat-based expanded breakfast cereal made from two oat lines to bind BA by using an in vitro simulated human digestion procedure will help assess processing-function relations of foods containing β-glucan. The aim of this work was to examine the impact of processing on the physical and sensory properties and on the in vitro bile-acid binding of two oat lines, one with high β-glucan concentration and one with a typical concentration. Understanding how β-glucan mediates processing and how oat genotype impacts the physical and sensory properties will allow oat breeders to target the most effective oat lines for further agronomic development to increase consumer benefits from oat as a functional food.

MATERIALS AND METHODS

Oat Flour

One experimental oat line, N979-5-2-4 (N979) developed at Iowa State University, and one publicly available cultivar, Jim, developed at the University of Minnesota, were grown in 2003 at

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the Agronomy and Agricultural Engineering Field Research Center near Ames, IA. The crops were harvested in August 2003, and the oats were dried and stored at 4°C with relative humidity of 40–50% in plastic bags before processing. Oats were shipped for milling to the Quaker Oats pilot plant located at Cedar Rapids, IA. The oat grains were dehulled with a Buhler aspirator, steamed for 1 min at 80°C and rolled to a flake thickness of 0.61 mm. The flakes were then ground into flour with a hammer mill through a 0.56-mm screen. Starch, protein, β-glucan, and lipid content of Jim and N979 oat flours were 63.3 and 54.4%, 12.1 and 20.1%, 4.8 and 8.1%, and 6.8 and 7.2%, respectively (Sayar et al. 2005). Moisture content of whole oat flours was determined by using Approved Method 44-15A (AACC International 2000). Previous work showed that β-glucan extracted from N979 had a molecular weight (MW) peak at 3.24 × 106, whereas β-glucan extracted from Jim had a MW peak at 2.73 × 106 (Sayar et al. 2005).

Oat Cereal Extrusion

The oat cereal formula (db) included 65.75% oat flour, 30% wheat starch (Midsol 50, MGP Ingredient Inc., Atchison, KS), 3% sugar, 0.25% salt, and 1% sodium bicarbonate. The oat cereal was produced at the Department of Grain Science and Industry, Kansas State University on a laboratory-scale, self-wiping, corotating, twin-screw extruder (model Micro-18, American Leistritz Extruder Co., Somerville, NJ) with an 18-mm barrel diameter and 30:1 L/D ratio. Jim oat lines were used to narrow the levels of the extrusion variables, including extrusion temperatures and moisture contents of feeding materials.

The extruder barrel was composed of six programmable temperature zones that are electrically heated and cooled by water circulation. Feed rate was set at 33.69 g/min and screw speed at 230 rpm. The temperature at zone 6 located near the die is referred to as the extrusion temperature. Extrusion temperatures evaluated in this study were 125, 150, 165, and 180°C. Temperatures of six barrel zones were increased incrementally, starting at 30°C for the first zone, to different expected temperature levels at the sixth zone. Moisture content levels studied included 16, 18, 25, 28, or 30%. Moisture contents of the ingredients were adjusted to expected values by adding an appropriate amount of water with a spray bottle to the dry ingredients in a mixer (Kitchen Aid, St. Joseph, MI) at the lowest speed and then further mixing at speed 2 for 5 min. An amount of 1 kg of ingredients was mixed at one time to ensure even distribution of water among the ingredients. After mixing, the contents in the mixer were sealed in a polyethylene bag and the moisture was equilibrated overnight in a 4°C refrigerator. The oat mixtures were allowed to warm to room temperature before extrusion the next day.

After preliminary trials, the extrusion variables were narrowed as described below. Once conditions for extrusion temperatures and moisture contents were chosen, a full-fractional-factorial design was conducted with the variables of extrusion temperature, moisture, and oat line. The expanded oat cereal was collected as a continuous strand after torque, barrel temperatures, and die pressure reached steady-state. Extruded cereal strands were cut manually into lengths of 15 cm and dried for 20 min in the oven at 100°C. The final product was sealed in plastic bags until needed for analysis.

The β-glucan concentration in the oat cereal was determined enzymatically using Approved Method 32-23 (AACC International 2000), with the mixed β-glucan linkage kit from Megazyme (Wicklow, Ireland). All analyses were done in duplicate and reported on a dry basis.

Expansion Ratio

Expansion ratio (ER) was calculated as the ratio of extrudate diameter to die diameter (2.3 mm). Data reported are the average of 10 measurements for each treatment.

Water Hydration

Water hydration (WH) of oat cereal was measured according to Approved Method 56–40 (AACC International 2000) with modification to account for a limited sample quantity. Oat cereal was cut into short pieces with lengths of 3–5 mm. The cereal pieces (2 g) were weighed and placed into a small beaker with 10 mL of distilled water, soaked for 1 min, and transferred to a clean, dried and preweighed U.S. no 25 sieve (Fisher Scientific, Cat. No. 14-306A). The hydrated pieces were uniformly spread onto the sieve, placed at a ~45° angle to facilitate water run-off, and drained for 5 min. Excess water was wiped from the lower rim of the sieve and the entire sieve containing hydrated pieces was reweighed. WH was reported as the amount of water retained per gram of dry material. The mean from three measurements for each treatment was reported.

Texture Analysis

The textural properties of oat cereal were measured using a texture analyzer (TA.XT2i, Texture Technologies Corp., Scarsdale, NY/Stable Micro Systems, Godalming, Surrey, UK). Oat cereals were randomly selected from each treatment and tested according to the settings reported by Yao et al. (2005). The peak force (g) reading was used as a measure of instrumental hardness. One measurement was applied to each of 10 separate cereal pieces from each treatment, with the data averaged for each treatment.

Sensory Evaluation

Three people evaluated cereals extruded at different temperatures and moisture contents to omit from further testing any products not suitable for eating because of undesirable characteristics such as extreme hardness. The group selected eight treatments of oat cereals extruded from these two oat lines at two temperatures and two moisture contents for presentation to a descriptive sensory panel. These eight treatments are described in Table I.

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**Table I: β-Glucan Percentages, Bile Acid (BA) Binding, and Sensory Properties of Oat Cereals Selected for Descriptive Sensory Evaluation**

<table>
<thead>
<tr>
<th>Cereal Temp Moisture</th>
<th>β-Glucan (% db)</th>
<th>BA Bindingb</th>
<th>Color</th>
<th>Hardness</th>
<th>Coarseness</th>
<th>Crunchiness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jim 165°C 16%</td>
<td>3.5 ± 0.1b</td>
<td>1.6 ± 0.2c</td>
<td>2.7 ± 1.0de</td>
<td>2.8 ± 1.5c</td>
<td>3.8 ± 1.4cd</td>
<td></td>
</tr>
<tr>
<td>Jim 165°C 18%</td>
<td>3.9 ± 0.1b</td>
<td>2.0 ± 0.1bc</td>
<td>3.9 ± 0.9bc</td>
<td>4.3 ± 1.2ab</td>
<td>5.2 ± 1.1ab</td>
<td></td>
</tr>
<tr>
<td>Jim 180°C 16%</td>
<td>3.4 ± 1.0b</td>
<td>1.6 ± 0.1c</td>
<td>2.2 ± 0.7c</td>
<td>2.8 ± 1.0x</td>
<td>3.6 ± 1.7d</td>
<td></td>
</tr>
<tr>
<td>Jim 180°C 18%</td>
<td>3.4 ± 0.3b</td>
<td>ndc</td>
<td>4.1 ± 0.8b</td>
<td>4.3 ± 1.2ab</td>
<td>4.9 ± 0.9ab</td>
<td></td>
</tr>
<tr>
<td>N979 165°C 16%</td>
<td>5.8 ± 0.3a</td>
<td>2.8 ± 0.3a</td>
<td>3.2 ± 0.9cd</td>
<td>3.3 ± 1.0bc</td>
<td>4.2 ± 1.2bcd</td>
<td></td>
</tr>
<tr>
<td>N979 165°C 18%</td>
<td>5.3 ± 0.1a</td>
<td>2.3 ± 0.2b</td>
<td>6.0 ± 1.0a</td>
<td>5.0 ± 0.8a</td>
<td>4.6 ± 1.1a</td>
<td>5.4 ± 0.8a</td>
</tr>
<tr>
<td>N979 180°C 16%</td>
<td>5.6 ± 0.2a</td>
<td>2.3 ± 0.4b</td>
<td>4.4 ± 1.0b</td>
<td>2.4 ± 0.8e</td>
<td>2.5 ± 1.4c</td>
<td>3.7 ± 1.1cd</td>
</tr>
<tr>
<td>N979 180°C 18%</td>
<td>5.4 ± 0.3a</td>
<td>1.0 ± 0.1d</td>
<td>5.4 ± 0.7a</td>
<td>4.1 ± 1.1ab</td>
<td>4.7 ± 1.1abc</td>
<td></td>
</tr>
<tr>
<td>Cheerios breakfast cerealb</td>
<td>3.5 ± 0.1b</td>
<td>0.6 ± 0.2d</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

a Scores for sensory evaluation are the average of 10 panelists.
b Bile acid (BA) binding (μmol/g of oat cereal, db).
c Not done due to limited amount of sample.

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A 10-member sensory panel composed of panelists with extensive experience in Quantitative Descriptive Analysis (QDA) was further trained during two sessions using standards representing two extreme ratings for each characteristic. The panelists were selected according to their willingness to participate and whether they normally consume cereals made of oat. Each characteristic was evaluated on a 10-cm line scale, with a low degree of the characteristic scored at 1 and a high degree scored at 10. The 10-point scale was chosen as directed by the sensory evaluation software (Compusense five v.4.6, Compusense, Ontario, Canada). During the official evaluations, panels received a measured portion (3 g) of cereals coded with a three-digit random number. Treatments were evaluated before and after adding milk (14.7 mL). Characteristics evaluated before adding milk were color (browness), hardness, coarseness, and roasted flavor. Characteristics of crunchiness and gumminess were evaluated after adding cereals to milk and allowing to mingle for 1 min.

Panelists rated each treatment by comparing it to standards for each characteristic and placing a vertical mark on the scale that indicated perceived value for each characteristic (Meilgaard et al 1999). A value of 1 for each characteristic was represented by Cheerios breakfast cereal (General Mills, Minneapolis, MN). Oat cereal made from Jim flour at 165°C and 21% moisture content was used as a standard with scores of 7 on the scales for brownness, hardness, coarseness, and crunchiness in milk. Cheerios breakfast cereal baked at 177°C for 4 min was used as a standard with a score of 5 for roasted flavor. Old fashioned oatmeal (52 g of oat flakes and 123 g of water stirred above the stove for 5 min at medium heat, then cooled) was used as the standard for gumminess with an assigned score of 7. Verbal descriptions were located at the two ends of the scale.

Treatments were presented to the panelists twice, following a randomized design in which each session consisted of eight samples and four standards. Panelists were seated in individual booths and provided with room-temperature water and unsalted crackers to clear the palate between sampling treatments. The scores reported in Table I are the averages of 10 panelists.

In Vitro Digestion and BA Binding

An in vitro digestion process was applied to the extruded oat cereals presented for sensory evaluation according to the method given by Beer et al (1997) with modifications. Cereal was milled in an ultracentrifugal mill (ZM-1, Retch GmbH & Co., Haan, Germany) fitted with a 0.5-mm sieve. Cereal powder (1 g, db) was mixed with 20 mL of sodium phosphate buffer (50 mM, pH 6.9) in a 50-mL centrifuge tube and stirred slowly at 37°C for 15 min. Stirring was continued for 15 min at 37°C after adding 100 μL of human salivary α-amylase (5 mg/mL in 3.6 mM CaCl2, Cat. No. A1031, EC 3.2.1.1, Sigma). Pepsin and pancreatin were added according to Beer et al (1997), with volume adjusted to the amount of cereals used. The BA mixture (4 mL, 1.2 μmol/mL in distilled water) containing sodium cholate, sodium deoxycholate, sodium glycocholate, and sodium taurocholate (Sigma) was added along with pancreatin (Sayar et al 2005). The digestion slurry was stirred slowly for 90 min at 37°C. Sodium phosphate buffer (15 mL, 50 mM, pH 6.9) was added to facilitate centrifuging at 3,100 × g for 20 min. Unbound BA in the supernatant after filtering through Whatman No. 4 filter paper was analyzed by using a BA diagnostic kit without dilution (Trinity Biotech, Bray Co., Wicklow, Ireland) and calculated based on a standard curve developed by using a BA mixture with different concentrations. A non-BA-binding negative control (cellulose) and a BA-binding anionic resin positive control (cholestyramine) from Sigma also were included for each set of analyses.

Statistical Analyses

A full-fractional-factorial design with levels chosen for both extrusion temperature and moisture content for each oat line was designed and the data analyzed by software (v.14, Minitab, State College, PA). Comparison of means was conducted by LSD at α = 0.05 (v.9.1, SAS Institute, Cary NC). Correlation analyses among properties also were conducted using Minitab v.14.

RESULTS AND DISCUSSION

Effect of Extrusion Conditions on Cereals Made from a Typical β-Glucan Oat

Flour from the traditional oat (Jim) with a typical % β-glucan was used in the trials designed to narrow the range of extrusion parameters for preparing oat cereals. Properties analyzed included ER, WH, and texture (Figs. 1–3).

Expansion ratio. When moisture content of the feeding material increased, ER of Jim oat cereal decreased at different rates for different temperatures (Fig. 1). This finding is consistent with previous research (Ilo et al 1996; Parsons et al 1996; Liu et al 2000; Onwulata et al 2001; Ding et al 2006). According to Ilo et al (1996), increasing moisture content decreased the specific mechanical energy (SME), apparent viscosity, and radial ER during extrusion of maize grits. Parsons et al (1996) reported a decrease in the ER of corn meal when the extrusion moisture content was increased from 19.5 to 21.5% (w/w). Kokini et al (1992) and Della Valle et al (1997) explained a sharp decrease in volumetric expansion with increased moisture content by the shrinkage and collapse of the extrudate after maximum expansion.
At 30% moisture content, cereal extruded at 125°C had a lower ER than when extruded at other temperatures. Cereal extruded at 180°C and 30% moisture content had a lower ER than cereal extruded at both 150 and 165°C, which may have been caused by the decrease in extrudate, because of low melt viscosity at the high temperature. There was no difference in expansion between 150 and 165°C when oat cereals were extruded at 30% moisture. While determining the optimum conditions for extrusion, moisture contents of ≥21% were tested at all temperatures. These higher moisture cereals had many dark brown spots on the surface, thus two lower moisture contents (16 and 18%) were included at extrusion temperatures of 165 and 180°C, but not for the lower extrusion temperatures. Previous research also suggested extrusion temperatures of ≥160°C were needed to produce extruded products with high ER values (Kokini et al. 1992).

For most moisture contents, cereal extruded at 165°C had a greater ER than at lower extrusion temperatures, and increasing extrusion temperature further did not necessarily increase ER (Fig. 1). Thus, 165°C seemed to be the optimum temperature to achieve high expansion at most moisture contents. Other extrusion studies have noted an increase in expansion with temperature to a specific optimum at 125–160°C, with further temperature increases causing either a decrease or no change, depending on the type of starch and moisture content (Chinnaswamy and Hanna 1988; Chinnaswamy and Prakash 1994; Cha et al. 2001; Moraru and Kokini 2003).

Although higher temperature leads to greater vapor pressure and increased driving force for expansion, it can also lead to a decrease in melt viscosity and, consequently, a greater degree of extrudate collapse (Cha et al. 2001). Bhattacharya and Prakash (1994) reported a significant quadratic effect of barrel temperature at 75–185°C on the expansion of rice flour extrudates. Chinnaswamy and Hanna (1988) and Chinnaswamy and Chinnaswamy (1993) observed a similar effect of barrel temperature at 105–200°C on expansion of extrudates from different kinds of native starches.

Water hydration. At 16% moisture, WH of cereal extruded at 165°C was not different from that extruded at 180°C (Fig. 2). However, when moisture content was increased to 18%, extruding at 180°C produced oat cereal with greater WH than at 165°C. At 125°C, increasing moisture from 28 to 30% lowered WH, whereas no significant difference was found for cereal extruded at 21–28%.

At the two highest extrusion temperatures (165 and 180°C), decreasing moisture by only 2% (from 18 to 16%) drastically and significantly increased WH from 1.2 to 2.0 and 1.6 to 2.2, respectively. The greatest difference between temperatures 165 and 180°C in WH was at 21% moisture. To summarize, at any specific moisture content, WH capacity increased with extrusion temperature and, in general, at any specific extrusion temperature WH decreased with increased moisture content (Fig. 2). These results might be explained by a combination of effects of starch gelatinization and degradation, and extrudate expansion. Higher WH might result from a greater extent of starch gelatinization (McPherson et al. 2000). WH also is greatly affected by the degree of porosity or expansion of the extrudate, as higher porosity and thinner cell walls in the extrudates lead to greater water absorption.

Hardness. There were no differences in hardness for cereal extruded at 165 and 180°C when moisture content was the same (Fig. 3). However, when extrusion temperature was decreased to 125 or 150°C, cereals were harder than at the two higher temperatures. Cereal extruded at 125°C with 30% moisture were harder than at all other conditions. At ≥21% moisture, hardness was greater than when extruded at 16 or 18% for extrusion temperatures of 165 and 180°C. The hardness of cereals increased with moisture content for each extrusion temperature and was consistent with the findings of Liu et al. (2000). In general, the hardness of extruded cereal exhibited an inverse relationship with extrudate expansion, as observed in several studies on extruded products where hardness was represented by instrumentally measured mechanical properties such as compression modulus and crushing stress (Hutchinson et al. 1987; Gogoi et al. 2000). This finding makes sense because a more expanded product has longer and thinner cell walls, which leads to ease in crushing of the product under compression (Gibson and Ashby 1997).

### Comparison of Effects of Extrusion Conditions on Cereals Made from High and Typical β-Glucan Oat Lines

Trials on the Jim oat line cereals extruded at moistures >21% or at extrusion temperatures of ≥150°C had a low ER (≤2.0) and a hard texture.

### Table II

<table>
<thead>
<tr>
<th>Expansion Ratio</th>
<th>Water Hydration</th>
<th>Hardness</th>
<th>β-Glucan (%)</th>
<th>Color</th>
<th>Hardness-Sensory</th>
<th>Coarseness</th>
<th>Crunchiness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oat type (OT)</td>
<td>0.34***</td>
<td>0.45***</td>
<td>2.04E+05</td>
<td>13.91***</td>
<td>55.95***</td>
<td>1.92ns</td>
<td>0.11ns</td>
</tr>
<tr>
<td>Extrusion temp (ET)</td>
<td>0.01ns</td>
<td>0.55***</td>
<td>2.49E+06*</td>
<td>0.03ns</td>
<td>10.88***</td>
<td>7.14**</td>
<td>1.86ns</td>
</tr>
<tr>
<td>Moisture (%)</td>
<td>0.75***</td>
<td>1.43***</td>
<td>1.80E+06***</td>
<td>0.01ns</td>
<td>6.22*</td>
<td>49.30***</td>
<td>44.40***</td>
</tr>
<tr>
<td>OT × ET</td>
<td>0.10**</td>
<td>0.22***</td>
<td>1.90E+05*</td>
<td>0.01ns</td>
<td>0.31ns</td>
<td>4.42*</td>
<td>2.02ns</td>
</tr>
<tr>
<td>OT × M</td>
<td>0.01ns</td>
<td>0.05 ns</td>
<td>5.49E+04</td>
<td>0.50*</td>
<td>0.61ns</td>
<td>0.01ns</td>
<td>0.01ns</td>
</tr>
<tr>
<td>ET × M</td>
<td>0.04*</td>
<td>0.08*</td>
<td>2.23E+05**</td>
<td>0.01ns</td>
<td>1.98ns</td>
<td>0.05ns</td>
<td>0.18ns</td>
</tr>
<tr>
<td>OT × ET × M</td>
<td>0.05*</td>
<td>0.09**</td>
<td>1.21E+05*</td>
<td>0.06ns</td>
<td>0.03ns</td>
<td>1.89ns</td>
<td>0.25ns</td>
</tr>
<tr>
<td>Error</td>
<td>0.01</td>
<td>0.02</td>
<td>4.24E+04</td>
<td>0.06</td>
<td>0.92</td>
<td>0.70</td>
<td>1.48</td>
</tr>
</tbody>
</table>

*Analyses were conducted based on two levels of extrusion temperature (160 and 180°C) and four levels of moisture (16, 18, 21, and 25%) for expansion ratio, water hydration, and hardness (texture analyzer). Two levels of extrusion temperature (160 and 180°C) and two levels of moisture (16 and 18%) were used for β-glucan content, color, hardness-sensory, coarseness, and crunchiness. Two oat types, Jim and N979, were included as a variable in analysis.

**a***, **, * = P < 0.001, P < 0.01, P ≤ 0.05, respectively; ns = not significant.
Thus, moistures of 16, 18, 21, and 25%, and extrusion temperatures of 165 and 180°C were selected for further tests on processing cereals from the two whole oat flours.

**Expansion ratio.** ANOVA results indicated moisture and oat type had an effect on ER (Table II). Extrusion temperature interacted with oat type and moisture. LSD analysis further indicated that cereals made from Jim oats had greater expansion than did cereal made from N979 oats at all moisture contents, except for 21%, when extruded at 165°C (Fig. 4). When extruded at 180°C, no difference occurred between these two oat lines, except at 21% moisture. The ER of cereal from both oat lines decreased when moisture content increased. Jim had a greater starch content (63.3%) than did N979 (54.4%). The higher starch content in Jim flour might be responsible for the greater ER of Jim cereal, with the greater amount of starch providing a more stretchable gas-holding matrix leading to increased expansion (Chen et al 2002). The N979 line tended to have a greater lipid content than did Jim but it was not significant (Sayar et al 2005). Most studies recognize that gelatinized starch plays a major role in expansion by providing the gas-holding capacity to the extrudate melt, whereas other ingredients such as proteins, sugars, fats, and fiber act as diluents or dispersed phase fillers that reduce the stretchability of the starchy matrix (Guy 1994; Moraru and Kokini 2003). Conway (1971) reported that the lower limit of starch content for good expansion is 60–70%. Although the difference in expansion ratios of these two oat lines might be mainly due to the starch composition difference, the higher protein content of N979 flour (20.1 vs. 12.1% in Jim) also may have contributed to a lower ER, caused by protein denaturation (Moraru and Kokini 2003).

**Water hydration.** ANOVA results suggested that all three main factors affected WH of cereals. Although moisture had no interaction with oat type, all other two- and three-way interactions affected WH of cereals (Table II). Generally, with similar extrusion temperatures and moisture contents, WH of Jim cereal was either greater than N979 cereal or there was no difference between the two oat lines (Fig. 5). For example, Jim cereal had greater WH than did N979 cereal at 16% moisture for both extrusion temperatures. The role of porosity in affecting WH was discussed above. Greater WH in Jim cereal is probably due to greater expansion or porosity as compared with N979 cereal.

For both oat lines, the extrusion temperature of 180°C resulted in greater or equal WH than at 165°C, regardless of moisture content, but Jim oats tended to show greater differences between the temperatures.

**Hardness.** Extrusion temperature, moisture, and oat type had similar effects on hardness of cereals as they did on WH (Table II). Hardness of cereal from both oat lines increased with an increase in moisture content from 16 to 21% at 165 and 180°C (Fig. 6). No difference in hardness occurred for Jim cereal extruded at either 165 or 180°C at 16% moisture, but for the N979 line, product extruded at 165°C was harder. When moisture was increased from 16 to 18% at 165°C, hardness of Jim cereal increased significantly, whereas no difference was found for N979 oat cereals. At moisture contents of 21 and 25%, differences in hardness between 165 and 180°C were greater for N979 cereal than for Jim oat cereal. Hardness is greatly affected by the expansion of the extrudates. The trends for hardness and the difference in hardness between cereal made from Jim and N979 flours can be explained on the basis of their expansion. The high water binding capacity of β-glucan in N979 cereal restricted water distribution during extrusion, likely causing reduced expansion and greater hardness in the final products as suggested by Grigelmo-Miguel et al (2001).

**Sensory Evaluations**

ANOVA analyses indicated that overall panel performance was consistent when evaluating cereal products for two replicates. Sensory panelists were a significant source of variation for all attributes analyzed, which is considered acceptable in most descriptive profiling procedures (Lapvetelainen and Rannikko 2000). Roasted flavor and gumminess of cereals were not significantly different. Thus, only color, hardness, coarseness, and crunchiness are discussed.
Color. ANOVA results indicated that the extrusion temperature, moisture, and oat type had an effect on the color of cereals, whereas no interactions were observed (Table II). Cereal made from both oat flours at 180 °C with 16% moisture were less brown than cereals extruded at all other conditions (Table I). N979 cereal was browner than Jim cereal under all conditions. A single extruded cereal exhibited notes of several hues depending on the textural characteristics (Lapvetelainen and Rannikko 2000). Brownness, described as a mixture of several hues, was selected for color evaluation as it best described the general surface color of the cereal. The browner color of N979 cereal may have been a result of less available water caused by the greater β-glucan concentration (Grigelmo-Miguel et al 2001). A lesser brown color of cereals extruded at higher temperatures and lower moisture contents was consistent with the findings of Gutkoski and El-Dash (1999).

Hardness. Oat type interacted with extrusion temperature to affect cereal hardness as evaluated by sensory panelists, although by itself, oat type did not show an effect (ANOVA results, Table II). For treatments from both oat lines, panelists rated oat cereal made at 18% moisture as harder than cereal made at 16% at both 165 and 180 °C (Table I). These results were consistent with hardness values of the cereal products determined by using the texture analyzer.

Coarseness. Only moisture affected the coarseness of cereals (ANOVA results, Table II). Extrusion temperature, oat type, or interactions of the two did not affect coarseness. Cereals made at 18% moisture were coarser than those made at 16% moisture for both oat lines (Table I). The feeding materials with N979 flour had almost twice as much β-glucan as did the Jim flour (5.3 vs. 3.2%), thus water available for extrusion was further deprived at 16% moisture. Low feed-moisture content increases the viscosity of material inside the extruder barrel, thus increasing the mechanical energy input, which might increase the degree of starch gelatinization and expansion (Gomez and Aguilera 1984). In our study, the greater the ER, the greater the puffiness and crispiness, and the lower the coarseness.

Crunchiness. Similarly to coarseness, only moisture affected cereal crunchiness (ANOVA results, Table II). Cereals made at 18% moisture were crunchier than those made at 16% moisture, likely resulting from a less puffy or airy structure and more resistance to water migration when soaked in milk (Table I).

β-Glucan Concentration and BA Binding
Extruded cereal treatments selected for sensory panel evaluations also were tested for β-glucan concentration and BA binding. Extrusion temperature and moisture did not affect final %β-glucan of the extruded cereal. Oat type and its interaction with moisture affected %β-glucan (Table II). Cereals made from N979 had greater β-glucan concentrations than did Jim cereals and Cheerios breakfast cereal (Table I). The N979 cereal, with more β-glucan in the original whole oat flour than Jim oat flour, had greater %β-glucan in the final products. Cheerios breakfast cereal was likely made from a commodity oat flour with 3.7–5.5% β-glucan (Miller et al 1993) and had a β-glucan concentration similar to that of Jim cereals. The %β-glucan in cereals from either oat line were not affected by extrusion conditions.

The amount of BA bound by the extruded cereals was lower than that bound by the original flours; BA binding of original Jim and N979 flours was 8.4 and 15.1 μmol/g (db), respectively (Sayar et al 2005). N979 cereal had the greatest BA binding when produced at 16% moisture and 165 °C, whereas Jim cereals did not differ in binding according to extrusion conditions (Table I). An increase in extrusion temperature from 165 to 180 °C at either moisture content decreased the BA binding of the N979 cereal. BA binding of Cheerios breakfast cereal was similar in value to N979 cereals made at 180 °C with 18% moisture. Cereals made from the two oat lines at other conditions had greater BA binding than did Cheerios breakfast cereal.

Correlations of Data from Oat Cereals
Correlations of oat cereal properties including ER, WH, and hardness measured by a texture analyzer, and six sensory attributes were analyzed for the eight treatments (Table III). Hardness rated by the sensory panel was positively correlated with coarseness (r = 0.946, P < 0.001) and crunchiness (r = 0.944, P < 0.001) of oat cereals. Also, oat cereal judged as harder had lower ER values (r = –0.799, P < 0.017) and WH values (r = –0.861, P < 0.006). Again, oat cereal judged as harder by the sensory panel also had greater hardness values as measured by the texture analyzer, but the correlation had a lower significance value than did other correlations (r = 0.647, P < 0.083). Oat cereals judged as gummier with milk were browner (r = 0.894, P < 0.003) and had higher β-glucan contents (r = 0.838, P < 0.009). Meanwhile, cereals with higher β-glucan content were browner (r = 0.821, P < 0.012). As rated by the sensory panelists, roasted flavor was negatively associated with hardness (r = –0.743, P < 0.035), crunchiness in milk (r = –0.799, P < 0.017), and coarseness (r = –0.785, P < 0.021). Cereal with a higher ER had stronger roasted flavor (r = 0.770, P < 0.025). Crunchiness of cereal had a greater positive relationship with hardness evaluated by panelists (r = 0.944, P < 0.001) than with that measured by the texture analyzer (r = 0.708, P < 0.050). Crunchiness also was positively associated with coarseness (r = 0.976, P < 0.001) and negatively correlated with WH (r = –0.908, P < 0.002) and ER (r = –0.725, P < 0.042). Cereal with higher WH ability also expanded more during extrusion (r = 0.733, P < 0.039). WH, ER, hardness, and crunchiness in milk of the extrudate are all related to the product structure.

Although N979 cereal produced at 165 °C with 16% moisture had the greatest BA binding, no significant correlations were found between BA binding and other properties. Previous research found that extrusion reduced insoluble fiber content of oat bran but increased soluble fiber content (Drzikova et al 2005). Other studies suggested that BA binding was positively related to insoluble dietary fiber percentage (Anderson 1995; Drzikova et al 2005). A few recent studies have demonstrated in vitro interactions of BA with either soluble or insoluble fibers from different sources, but the factors are not well understood (Dongowski and Ehwald 1999; Kahlon and Chow 2000). Current research in our laboratory on

| Table III: Correlations of Physical and Sensory Properties of Oat Cereals* |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Color                           | Hardness-Sensory| Coarseness      | Roasted Flavor  | Crunchiness     | Gumminess       | Water Hydration  |
| Coarseness                      | 0.946 (0.001)   | –0.785 (0.021)  | –0.799 (0.017)  |                 |                 |                 |
| Roasted flavor                  | –0.743 (0.035)  |                 |                 |                 |                 |                 |
| Crunchiness                     | 0.944 (0.001)   | 0.976 (0.001)   |                 |                 |                 |                 |
| Gummyness                       | 0.894 (0.003)   |                 |                 |                 |                 |                 |
| Water hydration                 | –0.861 (0.006)  | –0.831 (0.011)  |                 |                 |                 |                 |
| Hardness (g)                    | 0.647 (0.083)   |                 |                 |                 |                 |                 |
| β-glucan (%)                    | 0.821 (0.012)   |                 |                 |                 |                 |                 |
| Expansion ratio                 | –0.799 (0.017)  | –0.759 (0.029)  | 0.770 (0.025)   | –0.725 (0.042)  | 0.838 (0.009)   | 0.733 (0.039)   |

*Correlation coefficients with P values in parentheses.
oat lines with high β-glucan concentrations suggests that BA binding is a multicomponent-dependent process (Sayar et al. 2005). Thus, a mechanism for how extrusion might change the amount or structures of different components in oat cereals needs to be clarified by further studies.

CONCLUSIONS

Extrusion temperature and moisture had a significant effect on the physical and sensory properties of cereals made from two oat lines with different β-glucan concentrations. ER, WH, and hardness of cereals made from these oat lines at the same extrusion conditions differed. Cereals made from N979, the oat line with a high β-glucan concentration, had lower ER values and WH capacities than did cereals made from Jim oats, containing a typical β-glucan concentration. When moisture content of feeding material increased, ER values of cereals from both oat lines decreased at different rates for different extrusion temperatures. Extrusion at higher temperatures resulted in cereal with less hardness for both oat lines. Compared with cereal made from Jim oats and Cheerios brand breakfast cereal, cereal made from N979 oats was browner and had higher final β-glucan concentrations. Oat cereals made at 18% moisture were crunchier than at 16% moisture but extrusion temperature did not affect crunchiness of cereals made from either oat type. Cereal made from N979 oats at 165°C and 16% moisture had the best BA binding of all treatments, including the Cheerios cereal, and had crunchiness comparable to cereals made at other conditions. However, no correlations were found between BA binding and any other properties evaluated. Physiological function and sensory characteristics of oat cereals likely depend not only on the amount and MW of the β-glucan but also on the processing conditions of the product. A thorough understanding of the effects of extrusion conditions on cereal properties would assist in the best use of new oat genotypes with altered β-glucan concentrations and MW.

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LITERATURE CITED


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