

Rheological Properties of (1→3),(1→4)-β-D-Glucans from Raw, Roasted, and Steamed Oat Groats

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ABSTRACT

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Effects of hydrothermal treatments (steaming, roasting) of oat grain on β-glucan extractability and rheological properties were tested on oat cultivars with low (Robert) and high (Marion) β-glucan content. Steaming of grain reduced the amount of β-glucan that could be extracted, compared with raw or roasted grain, but the extracts from steamed grain had much greater viscosity. Increased extraction temperatures increased the amount and the average relative molecular mass (M_r) value of β-glucans extracted. In boiling water extractions, the average M_r values among raw, roasted and steamed oat samples were equivalent, but extracts from steamed oat grain had significantly higher intrinsic viscosity than the extracts from

roasted or raw oat grains. β-Glucan solutions purified from steamed grain extracts were very viscous and highly pseudoplastic, as described by the power law equation. Oat β-glucans from steamed samples were more viscoelastic than β-glucans from roasted or raw oat samples. Because viscous properties of β-glucans from boiling water extracts are influenced by hydrothermal treatments without affecting polymer molecular weight, polymer interaction with the solvent must be affected. Steaming may disrupt intramolecular cross-linkings in native β-glucan, allowing a linear chain configuration to generate greater viscosity.

The high nutritional value of oat (*Avena L.*) is one reason for its popularity and its increased human consumption (Welch 1995). The water-soluble dietary fiber (1→3),(1→4)-β-D-glucan (β-glucan) of oat is of particular importance to human nutrition because of its effect in lowering blood cholesterol level and reducing the risk of heart disease (Anderson et al 1984, Anderson and Gustafson 1988). The proposed mechanism for the hypocholesterolemic effect of water-soluble oat fiber appears to be related to the viscous properties of the high molecular weight β-glucan solutions. Increased gut viscosity by oat β-glucan may either impede the uptake of dietary cholesterol or inhibit bile salt reabsorption (Shinnick and Marlet 1993).

Hydrothermal treatments, including roasting and steaming of oat grain, are routine in the commercial processing of oat grain (Ganssman and Vorwerk 1995). The primary functions of these treatments are to inactivate lipid-degrading enzymes and to develop desirable flavors for the finished products. Hydrothermal treatments also affect the viscous properties of the oat flour slurries. Doehlert et al (1997) reported that the viscosity of oat flour slurries from steamed oat was significantly higher than the viscosity of oat flour slurries from roasted or raw oat grain. Steamed oat flour slurry viscosity increased with hydration time according to a hyperbolic function. The effect of oat grain steaming on oat flour slurry viscosity was partially reversed by the roasting treatment of oat grain and vice versa. This study also presented evidence that the hydrothermal treatments did not affect the molecular weight of the extracted β-glucan (Doehlert et al 1997).

The viscous properties of oat β-glucans are not only important for food applications, but are also significant for human nutrition (Autio et al 1987, Shinnick and Marlet 1993). The rheological properties of oat β-glucan have been subjected to a number of studies

(Autio et al 1987, 1992; Varum and Smidsrod 1988; Westerlund et al 1993; Wikstrom et al 1994; Doublier and Wood 1995), but the effects of hydrothermal oat grain heat treatments on the rheological properties of oat β-glucan have not yet been characterized. During oat grain heat-treatment, physicochemical properties of the β-glucans may be altered, and the rheological properties of the extracted β-glucans may therefore be changed. The objective of this research was to determine the effect of roasting (105°C, 2 hr) and steaming (20 min) of oat grain on oat β-glucan extractability and rheological properties of that soluble β-glucan.

MATERIALS AND METHODS

Oat Grain

Oat (*Avena sativa L.*, cvs. Marion and Robert) grain was obtained from Michael S. McMullen, Department of Plant Sciences, North Dakota State University, Fargo, ND. Samples were dehulled with a laboratory oat huller (Codema, Eden Prairie, MN) and were hand-picked to obtain hull-free groats. Oat groats were milled in a centrifugal mill (Retsch ZM-1, Brinkmann Instruments, Westbury, NY) fitted with a 0.5-mm collar screen to obtain oat flour.

Heat Treatments of Oat Grain

Heat treatments were applied to grain before dehulling and milling. Grain (250 g) was steamed in a vegetable steamer (260 × 170 mm) fitted with a lid by placing the grain in a metal basket suspended over boiling water for 20 min. The temperature of the live steam was determined to be 105°C. Roasting consisted of placing grain (250 g) in a glass dish (190 × 100 mm) and roasting in a convection oven at 105°C for 120 min. After heat treatments, grain was exposed to atmosphere at room temperature for 24 hr to allow moisture equilibration.

β-Glucan Extraction and Purification

β-Glucans were extracted from 5% (w/v) oat flour (dry basis) water slurries at 40, 65, and 100°C. The slurries were extracted for 1 hr under constant stirring. The insoluble solids were removed by centrifugation at 16,000 × g for 20 min.

Oat β-glucans were purified from boiling water extracts (120 mL) by digesting with 50 μL of amyloglucosidase (A-9913, Sigma Chemical Co., St. Louis, MO) at 50°C for 30 min, followed by precipitation of β-glucans with four volumes of 95% ethanol. The fibrous precipitate was collected by centrifugation at 10,000 × g for 20 min. Precipitated β-glucans were then freeze-dried and subsequently ground by a mortar and pestle into fine powders.

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Chemical Analyses

Starch content of oat groats was determined by Approved Method 76-11 (AACC 1995) with subsequent measurement of glucose with glucose oxidase.

Oat groat flour protein content was determined by the Kjeldahl procedure according to the Approved Method 46-12 (AACC 1995) using the catalyst described by Williams (1973). Protein conversion factor was 6.25. Moisture of oat groats and flours was determined by Approved Method 44-15A (AACC 1995). β -(1 \rightarrow 3), (1 \rightarrow 4)-D-Glucan content in oat flours was determined enzymatically according to McCleary and Glennie-Holmes (1985). Total lipid content of oat flour was determined by the extraction method of Bligh and Dyer (1959).

β -Glucan concentration in soluble extracts was determined enzymatically by the method of McCleary and Glennie-Holmes (1985). Protein concentration in the β -glucan extracts were measured by the Bradford dye-binding method (Bradford 1976) using commercially prepared reagents (Bio-Rad Laboratories, Hercules, CA) with bovine serum albumin as protein standard. Total carbohydrate content was determined by a colorimetric anthrone method (Hodge and Hofreiter 1962).

Relative Molecular Mass Estimation

The relative molecular mass (M_r) values of oat β -glucans were estimated from their elution during high-performance size-exclusion chromatography (HPSEC) using an HPLC system (HP 1090 Series II, Hewlett-Packard, Wilmington, DE) (TSK-GEL G 5000 PW_{XL}, TSK-GEL PW_{XL} guardcolumn, Tosohass, Montgomeryville, PA). The injection volume was 20 μ L. Deionized water was used as elution solvent and a refractive index detector (HP 1047A) was used for postcolumn detection. Dextran of known molecular weights (Pharmacia, Piscataway, NJ) were used as standards according to Wood et al (1991b). Standards used included Dextran T-70 (70,000 Da), Dextran T-200 (200,000 Da), and Dextran T-2000 (2,000,000 Da). An industrial-grade dextran (D-5501, Sigma) with molecular weights of 5,000,000 to 40,000,000 Da was used to determine the exclusion volume of the column. A commercial β -glucan preparation was obtained from Megazyme (Warriewood, NSW, Australia).

TABLE I
Chemical Composition (% db)^a of Oat Groats

| Cultivar | Starch | Protein ^b | Lipid | β -Glucan |
|----------|----------------|----------------------|---------------|-----------------|
| Marion | 61.0 \pm 0.3 | 14.9 \pm 0.1 | 6.7 \pm 0.3 | 6.0 \pm 0.1 |
| Robert | 67.3 \pm 0.2 | 13.6 \pm 0.2 | 5.8 \pm 0.1 | 4.2 \pm 0.2 |

^a Values are $n = 3$, \pm standard deviation.

^b $N \times 6.25$.

TABLE II
Effect of Genotype, Grain Pretreatment, and Extraction Temperature on Capillary Viscosity and Chemical Composition (mg/mL) of Crude-Filtered Soluble Extracts from Oat cvs. Marion and Robert

| | Viscosity ^a | β -Glucan | Carbohydrate | Protein ^b |
|------------------------|------------------------|-----------------|--------------|----------------------|
| Genotype | | | | |
| Marion | 48.1a ^c | 0.77a | 5.86a | 1.67a |
| Robert | 14.0b | 0.53b | 5.80a | 0.70b |
| Treatment | | | | |
| Raw | 16.6c | 0.72a | 5.81b | 1.12a |
| Roasted | 19.4b | 0.70a | 5.15c | 0.93b |
| Steamed | 57.1a | 0.54b | 6.52a | 0.75c |
| Extraction temperature | | | | |
| 40°C | 2.4c | 0.47c | 4.49c | 0.82b |
| 65°C | 2.9b | 0.55b | 4.97b | 0.86b |
| 100°C | 87.8a | 0.94a | 8.03a | 1.12a |

^a Measured using a capillary viscometer at 30°C. Values in centiStokes (cSt = cm²/sec $\times 10^2$).

^b $N \times 6.25$.

^c Values within a column and within a main effect followed by the same letter are not significantly different ($P > 0.05$).

Rheological Measurements

Semimicro capillary viscometers (Cannon-Ubbelohde, size 200 and 350, Jupiter Instruments, Jupiter, FL) were used to determine the viscosity of β -glucan extracts at 30°C. The intrinsic viscosities of purified β -glucans from boiling water extractions were determined from inherent viscosity using a size 75 viscometer according to Leach (1963). Six different β -glucan concentrations were used for every individual intrinsic viscosity measurement made.

The flow behavior of oat β -glucan extracts were determined by a viscometer (Haake VT 500, Fisons Instruments, Valencia, VA) at shear rates of 1–1,000/sec. The coaxial cylinder sensor (sensor system NV) was used and the temperature was controlled to 30°C. Data were fitted into power law equation: $\sigma = k \gamma^n$; where σ is the shear stress (N/m²), γ is shear rate (1/sec), k is a consistency index (N sec ^{n} /m²), and n is a dimensionless constant that indicates deviation from Newtonian flow.

Shear viscosity was also measured with a rheometer (CSL 100, Carri-Med Ltd, Surrey, England). A cone and plate attachment (4 cm diameter, 2° cone angle) was used and the measurements were conducted at 25°C. Shear rate sweep was performed by scanning the samples from low (1/sec) to high shear (1,000/sec) and then from high back to low shear rate within 2 min.

Viscoelastic properties of the purified β -glucans were also measured with the same instrument under dynamic condition (oscillatory shear). The measurement was conducted at 25°C and the measurement condition (frequency range 0.1–20 Hz, torque 100 μ N/m) was verified to be within the limits of linear viscoelastic region.

Statistical Analyses

Experiments, including hydrothermal treatments and extractions, were conducted in triplicate. Results were analyzed using a Statistical Analysis System computer program (SAS Institute, Cary, NC). Analysis of variance (ANOVA) was performed using the general linear model (GLM) procedure of SAS where all factors were considered fixed. Duncan's new multiple range test ($\alpha = 0.05$) was used to differentiate treatment means determined to be significantly different. Error bars on figures represent standard deviation of means. Where error bars are not visible, standard deviation was smaller than the line symbol.

RESULTS AND DISCUSSION

Chemical Composition of Oat Groats

The oat cultivars Robert and Marion (4.2 and 6.0% β -glucan, respectively) were chosen for this study because of the divergence in β -glucan concentration in their groats (Table I). Starch, protein, and lipid concentrations were also determined for these oat cultivars.

TABLE III
ANOVA^a Comparing Effects of Genotype, Grain Pretreatment, and Extraction Temperature on Oat Soluble Extract Viscosity and Composition

| Source | df | Viscosity ^b | β -Glucan | Carbohydrate | Protein ^c |
|-----------------------|----|------------------------|-----------------|--------------|----------------------|
| Genotype (G) | 1 | 14,891** ^d | 0.8510** | 0.0356 | 2.9167** |
| Pretreatment (P) | 2 | 8,575** | 0.1639** | 8.4499** | 0.6108** |
| Temperature (T) | 2 | 41,953** | 1.0986** | 66.4658** | 0.4865** |
| $G \times P$ | 2 | 1,598** | 0.0059 | 5.1094** | 0.2345** |
| $G \times T$ | 2 | 14,205** | 0.5396** | 1.2880** | 0.0298 |
| $P \times T$ | 4 | 8,034** | 0.0764** | 35.4742** | 0.6741** |
| $G \times P \times T$ | 4 | 1,535** | 0.0067 | 2.0216** | 0.1871** |
| Error | 36 | 0.4 | 0.0074 | 0.0772 | 0.0146 |

^a Analyses of variance (mean squares). df = Degrees of freedom.

^b Measured using a capillary viscometer at 30°C. Values in centiStokes (cSt = cm²/sec $\times 10^2$).

^c $N \times 6.25$.

^d *,** = $P < 0.05$, $P < 0.01$, respectively.

Oat β -Glucan Extractability and Extract Properties

Samples of Marion and Robert oat were steamed, roasted, or not treated. Water-soluble extracts were made at 40, 65, and 100°C. Crude-filtered extracts were analyzed for capillary viscosity, β -glucan concentration, protein concentration, and total carbohydrate concentration (Table II). ANOVA of the results indicated that genotype, grain pretreatment, and extraction temperature significantly ($P < 0.01$) affected the amount of β -glucan extracted, the viscosity of the extracts, and the protein concentration in the extracts (Table III). Carbohydrate concentration of the extracts was not significantly affected by genotype but was significantly affected by pretreatment and extraction temperature.

Capillary viscosity of Marion extracts was consistently greater than that of Robert with the corresponding treatment (Table II). This is consistent with the higher β -glucan concentration in Marion groats than in Robert groats (Table I) and with a previous report that Marion groat flour slurries had greater viscosity than that of Robert oat flour slurries (Doehlert et al 1997). Capillary viscosity was lowest in extracts from raw samples and was much higher in extracts from steamed samples (Table II). Capillary viscosity of extracts at 65°C was slightly greater than the viscosity of extracts made at 40°C, although the capillary viscosity of extracts made at 100°C was much greater than either of these. The genotype-by-pretreatment, genotype-by-temperature, pretreatment-by-temperature, and genotype-by-pretreatment-by-temperature interactions were all significant for capillary viscosity (Table III), and the interactions were accountable by differences in magnitude of responses.

The β -glucan concentration was consistently higher in extracts from Marion groats than in extracts from Robert oats. This is consistent with the relative β -glucan concentration in Marion and Robert groats (Table I). β -Glucan concentration was not significantly different among raw and roasted samples, but was consistently lower in extracts from steamed samples. There were only small differences in β -glucan concentration between 40 and 65°C extraction temperatures, but much greater amounts of β -glucan were recovered from boiling water extractions (Table II). The genotype-by-temperature and pretreatment-by-temperature interactions were significant for β -glucan concentration (Table III) and were due to differences in magnitude of responses.

Extraction temperature was the major factor affecting total carbohydrate concentration in soluble extracts (Table III), where greater concentrations of carbohydrates were extracted at higher temperatures (Table II). Genotype-by-pretreatment, genotype-by-temperature, pretreatment-by-temperature, and genotype-by-pretreatment-by-temperature interactions were all significant (Table III) and appeared to be entirely due to differences in magnitude of responses.

Marion extracts had consistently higher protein concentration than did Robert extracts (Table II). Marion groats also contained a higher concentration of protein than did Robert groats (Table I). More protein was extracted from raw oat flour than from roasted or steamed treatments and at the 100°C extraction temperatures. The significant

interactions (Table III) were attributed to differences in the magnitude of the responses.

The results concerning the effect of extraction temperature on β -glucan extraction and capillary viscosity are consistent with several previous reports (Fleming and Kawakami 1977, Wood et al 1978, Ahluwalia and Ellis 1985).

Wood et al (1991a) also reported that more β -glucans were released from oat that was not heat-treated than from the heat-treated samples. It is established that nearly all of the viscosity of an oat extract is caused by the β -glucan in solution (Wood et al 1978, Bhatti 1992). Because the extracts from raw oat had higher β -glucan concentrations than steamed oat extracts, and the extract viscosities of steamed oat samples were significantly ($P < 0.05$) higher than raw or roasted extracts (Table II), there must have been a physical difference in β -glucans extracted from raw, steamed and roasted oat grains. Wikstrom et al (1994) also observed that the apparent viscosity of β -glucan extract from steam-flaked oat was much higher than the apparent viscosity of β -glucan extract from untreated oat. They concluded that the viscosity difference was caused by β -glucan concentration, but not by the functional property of β -glucans.

The M_r values of oat β -glucans in the oat extracts are given in Table IV. Extraction temperature was the strongest factor affecting the M_r of extracted β -glucans (Table III). The boiling water extracts contained β -glucans with the highest M_r values (Table IV). This is consistent with previous reports (Fleming and Kawakami 1977, Varum and Smidsrod 1988). Higher extraction temperature may allow for extraction of higher M_r polymers, or β -glucan polymers may be degraded by the enzymes or microbes at the 40 and 60°C extraction temperatures. However, using boiling water extraction, β -glucans from raw, roasted, and steamed oat samples had similar M_r values. This is consistent with our earlier study (Doehlert et al 1997). The M_r of commercial β -glucan from Megazyme was much smaller than that of β -glucans from boiling water extractions. The M_r values reported here (Table IV) for the boiling water extraction are similar to those reported by Wood et al (1991b) for water extracts from oat.

The results indicated that the viscosity differences between β -glucans from steamed and roasted oat samples were not due to β -glucan molecular weight. Other physical properties, such as molecular configuration or water-binding capacity of the β -glucans must have been responsible for the differences.

Chemical Composition of Purified β -Glucans

β -Glucan solutions were purified, lyophilized, and analyzed for the composition of the solids. The results (Table V) indicate that the amyloglucosidase digestion and ethanol precipitation process removed significant amounts of other carbohydrates from β -glucans from boiling water extractions. There was 8–10% protein present in the lyophilized β -glucan preparations. Preparations from roasted oat groats contained a greater β -glucan concentration than those from steamed oat grains. Oat β -glucan preparations from steamed oat grains contained higher amounts of proteins than β -glucans from roasted grains. But protein and starch concentrations were small when compared to the β -glucan concentration (Table V), which was responsible for the observed viscosities.

TABLE IV
Estimations of M_r for Oat β -Glucans from Different Extraction Temperatures Based on Size-Exclusion HPLC^a

| Sample (cultivar) | 40°C | 65°C | 100°C |
|----------------------------------|-------------------|--------|---------|
| Raw (Marion) | 415b ^b | 1,664b | 2,391a |
| Roasted (Marion) | 478b | 1,578b | 2,323ab |
| Steamed (Marion) | 1,024a | 1,810a | 2,211b |
| Raw (Robert) | 118b | 985b | 2,342a |
| Roasted (Robert) | 222b | 1,072b | 2,369a |
| Steamed (Robert) | 581a | 1,919a | 2,266a |
| Oat β -glucan (commercial) | ... | 450 | ... |

^a Molecular mass estimations expressed relative to dextran standards of 70, 200, and 2,000 kDa. Industrial dextran with average molecular weight of 5,000 to 40,000 kDa was used to determine the exclusion volume of the column.

^b Values within a column and within an oat cultivar followed by the same letter are not significantly different ($P > 0.05$).

TABLE V
Chemical Composition (%) of Purified and Lyophilized Oat β -Glucans from Boiling Water Extractions

| Sample (cultivar) | β -Glucan | Starch | Protein ^a |
|-------------------|--------------------|--------|----------------------|
| Raw (Marion) | 83.3b ^b | 0.55a | 9.30a |
| Roasted (Marion) | 85.3a | 0.70a | 8.08b |
| Steamed (Marion) | 83.9b | 0.78a | 9.11a |
| Raw (Robert) | 86.3a | 0.58b | 8.72b |
| Roasted (Robert) | 87.7a | 0.76a | 7.95c |
| Steamed (Robert) | 84.2b | 0.74a | 10.04a |

^a N \times 6.25.

^b Values within each oat cultivar and within a column followed by the same letter are not significantly different ($P > 0.05$).

Rheological Characterization

Intrinsic viscosity is essentially a measure of the internal friction or resistance to flow of high-polymeric molecules in solution. The intrinsic viscosity of the purified oat β -glucans from steamed, roasted, and raw oat grain (Table VI) indicated that β -glucan solutions from steamed oat samples had significantly higher intrinsic viscosity than β -glucan solutions from roasted or raw oat ($P < 0.05$) in either dimethyl sulfoxide (DMSO) or water solvent systems. Because DMSO is a more polar and hygroscopic solvent than water, β -glucan intrinsic viscosity in DMSO was generally less than the corresponding intrinsic viscosity in water (Table VI). The effects of grain heat treatments on intrinsic viscosities of purified β -glucan solutions is consistent with the effects observed with the crude extract capillary viscosity results (Table II).

The empirical correlation between intrinsic viscosity and molecular weight for linear polymers can be described by the Mark-Houwink equation (Billmeyer 1984): $[\eta] = K'M^a$, where $[\eta]$ is intrinsic viscosity and M is polymer molecular weight. Both K' and a are constants that are affected by solvent as well as the polymer types. Generally, for the same polymer species, higher molecular weight will result in higher intrinsic viscosity. At boiling water extraction conditions, β -glucans from oat groats with different heat-treatment histories had similar molecular weights (Table IV), but their intrinsic viscosities were significantly different (Table VI). These results suggested that heat-treatments of oat grain physically or chemically modified oat β -glucan polymers without changing the β -glucan molecular weights. It had been reported that the constant a in the Mark-Houwink equation reflects the molecular configuration of the polymer chain in a solution (Billmeyer 1984, Varum and Smidsord 1988). Hydrothermal treatment of oat grain appears to affect the oat β -glucan polymer chain conformation in solution. We hypothesize that the β -glucan polymer chain may have intramolecular associations through hydrogen bonding. Steaming of oat grain may break the intramolecular associations of oat β -glucan and

make the polymer assume an extended linear chain conformation. The linear conformation of β -glucan generates a larger hydrodynamic volume in solution and, thus, may increase solution viscosity.

The flow behavior of the purified β -glucans from heat-treated oat grains was evaluated by the power law equation (Table VII). The results indicated that steaming of oat grain affected the flow behavior of oat β -glucans. Smaller value of flow behavior index n reflects more deviation from the Newtonian flow. Purified oat β -

TABLE VI
Effect of Oat Grain Heat Treatments
on β -Glucan Intrinsic Viscosity^a

| Sample (cultivar) | DMSO | Water |
|----------------------------------|--------------------|-------|
| Raw (Marion) | 5.60c ^b | 8.0c |
| Roasted (Marion) | 6.52b | 10.5b |
| Steamed (Marion) | 7.91a | 11.7a |
| Raw (Robert) | 5.14c | 7.48c |
| Roasted (Robert) | 6.27b | 8.03b |
| Steamed (Robert) | 7.44a | 9.11a |
| Oat β -glucan (commercial) | 3.92 | 4.34 |

^a Measured using a capillary viscometer at 30°C. Values in centiStokes (cSt = cm²/sec $\times 10^2$). Intrinsic viscosities (dL/g) were calculated by plotting inherent viscosity vs. β -glucan concentration. DMSO = dimethyl sulfoxide.

^b Values within a column and within an oat cultivar followed by the same letter are not significantly different ($P > 0.05$).

TABLE VII
Effect of Oat Grain Heat Treatments on the Power Law Constants^a
of Oat β -Glucan in DMSO Solution^b

| Sample (cultivar) | k | n | R^2 |
|----------------------------------|-------------------|-------|-------|
| Raw (Marion) | 126c ^c | 0.71a | 0.99 |
| Roasted (Marion) | 147b | 0.71a | 0.99 |
| Steamed (Marion) | 235a | 0.64b | 0.99 |
| Raw (Robert) | 80c | 0.76a | 0.99 |
| Roasted (Robert) | 115b | 0.73a | 0.99 |
| Steamed (Robert) | 153a | 0.61b | 0.99 |
| Oat β -glucan (commercial) | 30 | 0.96 | 0.99 |

^a k = Consistency index (N sec ^{n} /m²), n = dimensionless constant that indicates deviation from Newtonian flow, R^2 = correlation coefficient. Measurements were made using a viscometer with a coaxial cylinder sensor at 30°C.

^b Dimethyl sulfoxide.

^c Values within a column and within an oat cultivar followed by the same letter are not significantly different ($P > 0.05$).

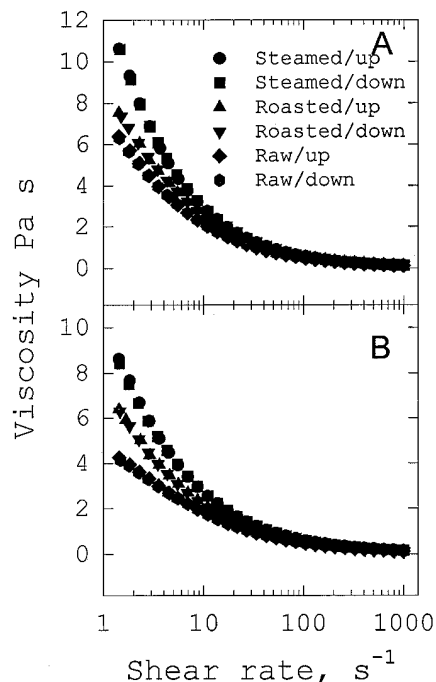


Fig. 1. Effect of oat grain heat treatment on the shear viscosity of β -glucans (1.5% [w/v] in dimethyl sulfoxide) extracted from cvs. Marion (A) and Robert (B).

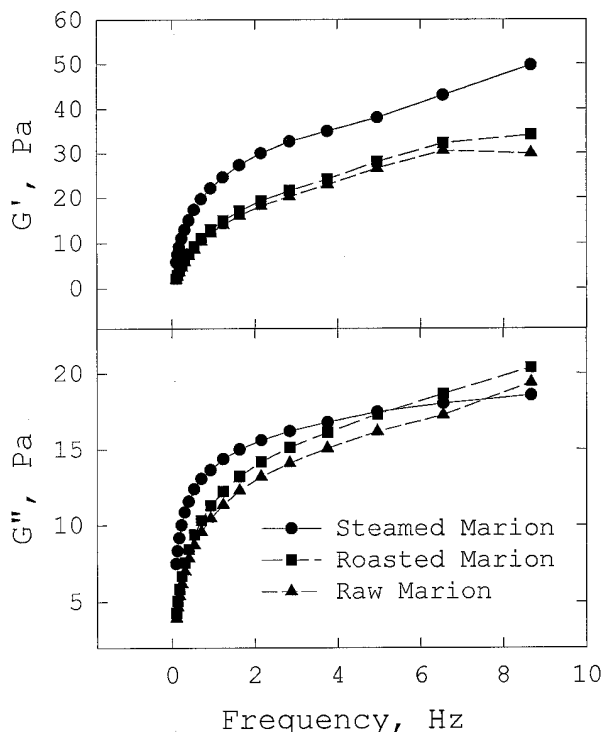


Fig. 2. Effect of heat-treated Marion oat grain on β -glucan (1.5% [w/v] in dimethyl sulfoxide) viscoelastic properties. G' = elastic (storage) modulus; G'' = viscous (loss) modulus.

glucans from steamed oat grains were more highly pseudoplastic than the β -glucans from roasted or raw oat grains (Table VII). No thixotropic properties were observed for any of the β -glucan preparations (Fig. 1).

Changes in rheological properties of a polymer reveal changes in its molecular structure. Therefore, rheological measurements can

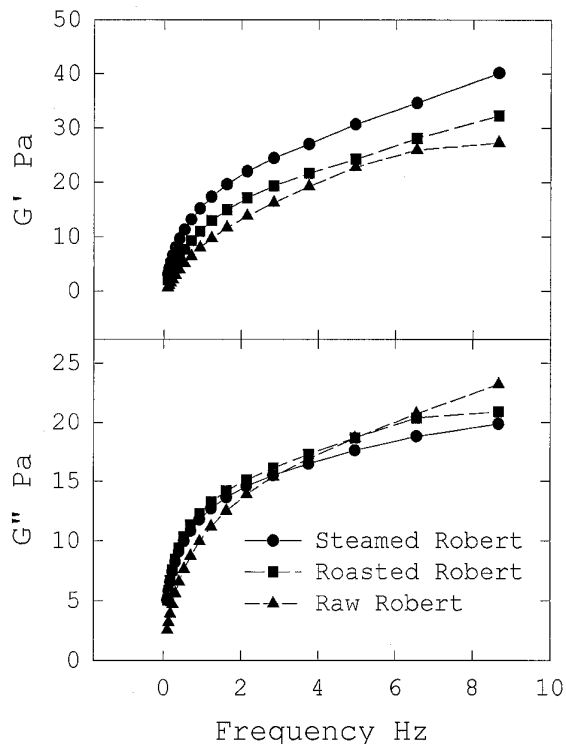


Fig. 3. Effect of heat-treatment of Robert oat grain on β -glucan (1.5% [w/v] in dimethyl sulfoxide) viscoelastic properties. G' = elastic (storage) modulus; G'' = viscous (loss) modulus.

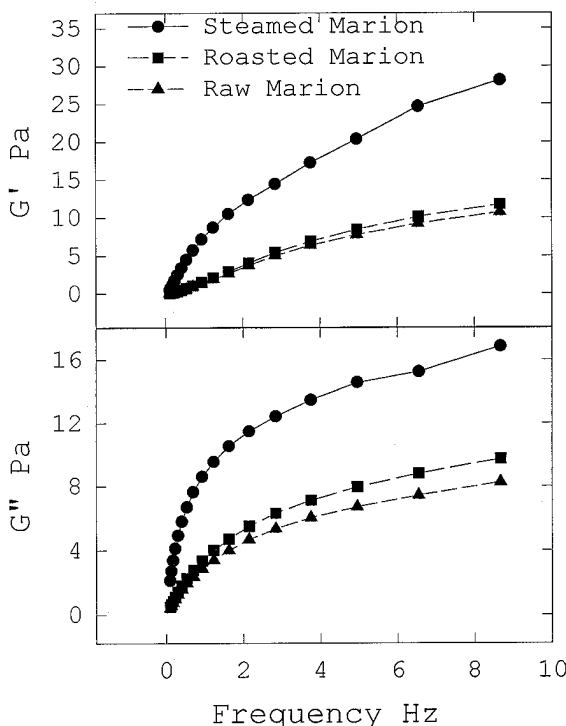


Fig. 4. Viscoelastic properties of β -glucan solutions (1.0% [w/v] in water) from heat-treated Marion oat. G' = elastic (storage) modulus; G'' = viscous (loss) modulus.

provide a means of monitoring changes in polymer structure after certain treatments. Dynamic oscillatory rheometers can simultaneously measure the elastic (storage modulus G') as well as the viscous (loss modulus G'') components of a material's complex viscosity and can assess the frequency-dependent properties of the materials being tested (Weipert 1990). The mechanical spectra (changes of G' and G'' as a function of oscillation frequency) of Marion and Robert oat (1.5% w/v solution) β -glucans in DMSO with different heat-treatment histories are shown in Figs. 2 and 3. Steaming of oat grain resulted in β -glucans with higher elasticity (higher G' values) as compared to β -glucans from roasted or raw oat. However, the viscous component (G'') of steamed oat β -glucan solutions varied only slightly from the roasted or raw β -glucan solutions. At higher measurement frequency, β -glucans from steamed oat samples exhibited lower G'' than the β -glucans from raw or roasted oat samples. β -Glucan preparations from steamed oat grain interacted with DMSO solvent differently when compared to β -glucans from roasted or raw oat grains.

When water was used as a solvent, both elastic (G') and viscous (G'') properties of oat β -glucans from steamed grain were higher than β -glucans from roasted or raw oat grains (Figs. 4 and 5). Solvent had significant effects on β -glucan polymer rheological behaviors (Figs. 2–5). However, with both solvent systems, β -glucans from steamed samples exhibited more elasticity and behaved differently with increasing frequency than did β -glucan from roasted or raw oat samples. The results further supported our hypothesis that heat-treatment of oat grain induced certain changes in the physical structures of oat β -glucan polymers and thus affected its rheological properties.

CONCLUSIONS

Oat grain is routinely kilned and steamed before milling to develop unique flavors and to inactivate lipid-degrading enzymes. In this study, heat-treatments of oat grain affected the extractability and rheological properties of oat β -glucans. Lesser amounts of β -glucans were extracted from steamed oat samples, but the steamed extract

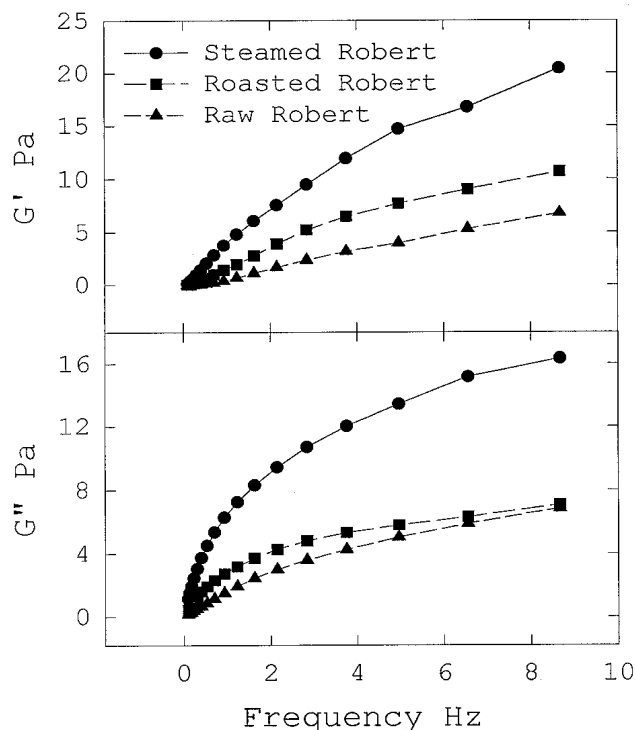


Fig. 5. Viscoelastic properties of β -glucan solutions (1.0% [w/v] in water) from heat-treated Robert oat. G' = elastic (storage) modulus; G'' = viscous (loss) modulus.

viscosities were significantly higher at all extraction conditions. Heat treatment of oat grain did not affect the molecular weight of oat β -glucans. However, oat β -glucans from steamed oat grain had significantly higher intrinsic viscosity, were more pseudoplastic, and were more viscoelastic (higher G' and G'') than β -glucans from roasted and raw oat grains.

Our results suggest that heat treatment of oat grain affected physical properties of the β -glucan polymer, such as molecular conformation. Oat β -glucans may exist with intramolecular hydrogen bonding in their natural state. Dry heat treatment (roasting) may increase the intramolecular association, whereas moist heat (steaming) may break these associations, replacing intramolecular bonding with water binding. With the same M_r , an extended linear β -glucan configuration would have larger hydrodynamic volume, would be more pseudoplastic, and also would be more viscoelastic, which is consistent with the experimental results reported here.

The rheological properties of oat β -glucans have nutritional and functional importance in the use of oat products toward food, feed, and industrial applications. It may become desirable to apply specific heat treatment to oat grain to generate products of specific rheological properties to meet needs of specific applications.

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