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Rheological Properties and Baking Performance of New Oat β-Glucan-Rich Hydrocolloids

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Two new oat β-glucan hydrocolloids (designated C-trim20 and C-trim30) obtained through a thermal-shearing process were evaluated for their potential use in food products as functional ingredients. Their rheological characteristics were investigated using steady and dynamic shear measurements. Both samples exhibited typical shear-thinning and viscoelastic properties of random coil polysaccharides. The Cross equation was also used to examine the dependence of their apparent viscosity on shear rates. Furthermore, the effects of flour replacement with C-trim20 on the physical, rheological, and sensory properties of cookies were studied. The cookies containing C-trim20 exhibited reduced spreading characteristics compared with the control due to their increased elastic properties. Also, higher water content and water activity were observed in the C-trim20 cookies. However, flour replacement with C-trim20 up to 10% produced cookies with instrumental texture properties similar to those of the control, which was in good agreement with the sensory results.

KEYWORDS: Oat; β-glucan; hydrocolloids; cookies; rheology; sensory evaluation

INTRODUCTION

Hydrocolloids are mainly hydrophilic biopolymers with high molecular weight that have high water retention capacity and unique functionalities such as thickening, gelling, and emulsifying properties. They are extensively used in a variety of food applications to control the rheology and texture of food products (*1*), reduce calories by replacing fat (*2*), modify starch gelatinization and retrogradation (*3*, *4*), and also provide freezing/thawing stability (*5*). Thus, the utilization of new hydrocolloids can provide more opportunities to create new food products and improve food quality in the food industry.

Recently, new oat hydrocolloids, designated C-trims (C stands for calorie) have been developed by the U.S. Department of Agriculture (*6*). They were prepared by steam jet-cooking and fractionating oat bran. Like typical hydrocolloids, they can be used to control the rheology and texture of food products. Moreover, they can improve nutrition because they have a high content of β-glucan, ranging from 15 to >50%. In particular, C-trim20 and C-trim30 have 20 and 30% β-glucan, respectively. They can be therefore used in food products to add health benefits such as lowering cholesterol, even making a health claim possible on food labels (*7*).

The purpose of this study was to characterize the rheological properties of two new oat hydrocolloids, C-trim20 and C-trim30, and to evaluate the performance of C-trim20 in cookie baking. For the baking study, the flour in cookie dough was partly replaced with C-trim20 and the quality attributes of the cookies were examined with respect to their physical, rheological, and sensory properties.

MATERIALS AND METHODS

Preparations of C-trim20 and C-trim30 Hydrocolloids. C-trim20 and C-trim30 were obtained according to the following procedures: Oat bran concentrate (100 g, Quaker Oats Co., Chicago, IL, lot 18608408, item 26629) was slurried in water (1900 mL) at pH 6.55. The slurry was blended by using a colloid mill (4000 rpm, 60 min, Polythron PT6000 with Aggregat PT-DA-6060/2WEC, Brinkmann Instruments Inc., Westbury, NY) and then passed through a 400 mesh sieve. The sieve liquid was centrifuged at 1590*g*, and the supernatant was mixed with the separated sieve solids. This reconstituted slurry was steam jet-cooked (65 psi, 285 °F, 1.2 L/min flow rate) and passed through a 200 mesh sieve. For C-trim20, half of the separated liquid was drum-dried to give a composition of β-glucan, 20.9%; protein, 27.0%; starch, 39.0%; total lipid, 7.2%; and ash, 4.0%, on a dry basis. For C-trim30, the other half of separated liquid was centrifuged at 1590*g* for 15 min before being drum-dried, yielding a composition of β-glucan, 32.0%; protein, 14.4%; starch, 45.3%; total lipid, 2.3%; and ash, 4.8%, on a dry basis. The C-trim samples were stored at −18 °C in a plastic bag until used and tested.

Cookie Preparations. The formulations for control cookies consist of 225 g of pastry flour (Siemer Milling Co., Teutopolis, IL), 72 g of sugar (C&H Sugar Co. Inc., Crockett, CA), 22.5 g of brown sugar (Imperial Sugar Co., Sugar Land, TX), 2.3 g of nonfat dry milk (Dairy America, Fresno, CA), 2.3 g of sodium bicarbonate (Kroger Co., Cincinnati, OH), 100 g of shortening (Crisco, The J. M. Smucker Co., Orrville, OH), 3.4 g of high-fructose corn syrup (Cargill, Eddyville, IA), 2.8 g of salt, 1.1 g of ammonium bicarbonate, and 49.5 g of water. The composition of the pastry flour used in this study is as follows: 13% moisture, 78.1% carbohydrates, 7.4% protein, 1% fat, and 0.48% ash. For C-trim20 cookies, the pastry flour (10, 20, and 30 wt %) was

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replaced with three parts of C-trim20 and two parts of water. C-trim20 in a dry powder was mixed with the flour, and the water was added to the formulation water.

All dry ingredients except flour and C-trim20 were tumbled in a jar, transferred into a KitchenAid mixer (St. Joseph, MI) with a paddle beater, and mixed with shortening for 3 min on speed 1. The bowl and paddle beater were scraped every minute. The mixture of high-fructose corn syrup and water in which ammonium bicarbonate was dissolved was added into the mixing bowl and mixed for 1 min on speed 1. After scraping down, the mixing was continued for an additional minute on speed 2. The mixture of flour and C-trim20 was then added and blended for 2 min with scraping every 30 s. The cookie doughs were sheeted to a thickness of 7 mm and cut with a cookie cutter of 6 cm diameter. They were baked at 205 °C in a reel oven for 11 min. After cooling, they were packaged and stored at room temperature in a plastic bag.

Rheological Measurements of C-trim Suspensions and Cookie Dough. Samples were prepared by dispersing C-trim20 and C-trim30 in water at a range of concentration from 3 to 11%. They were kept at 80 °C for 20 min, cooled, and then transferred to a stress-controlled rheometer (AR2000, TA Instruments, New Castle, DE), which was operated at 25 °C with a 60 mm parallel plate. The shear viscosity was measured at a range of shear rates from 0.01 to 1000 s^{-1}, and the dynamic oscillatory testing was performed as a function of frequency (0.1−100 rad/s). The used strain (0.1%) was in the linear viscoelastic limit.

For the rheological measurements of cookie dough, a strain-controlled rheometer (ARESLSM, TA Instruments) equipped with two 25 mm serrated plates was used. Frequency sweep was carried out at 25 °C from 0.1 to 100 rad/s under a 0.5% strain level, which was within the linear viscoelastic region of all cookie samples. In addition, cookie dough samples without sodium bicarbonate and ammonium bicarbonate were heated from 30 to 90 °C at a rate of 5 °C/min, and their dynamic viscoelastic properties were scanned at a frequency of 1 rad/s and a strain of 0.05%. Before rheological testing, the dough sample rested at room temperature for 10 min.

All rheological curves reported in this study are the mean values of at least two measurements.

Physical, Textural, and Sensory Properties of Cookies. Measurement of the diameter and height of a cookie was made according to the AACC method (10-54). A moisture analyzer (130 °C, 30 min, Mettler Toledo, Greifensee, Switzerland) and an Aqua Lab water activity meter (Decagon Devices Inc., Pullman, WA) were used to measure the moisture content and water activity of cookies, respectively.

The texture properties of cookies were investigated by using a Texture Analyzer (Texture Technologies Co., Scarsdale, NY). Cookie samples were penetrated with a flat probe of 4 mm diameter at a crosshead speed of 5 mm/s. Probing was carried out at three different places on a cookie, and the maximum peak force and the peak distance were recorded from the force/time curves. The textural measurements were triplicated over 3 days.

A 15 member sensory panel experienced in evaluating the flavor and texture of foods was trained for the sensory analysis of cookies. During a 3 week training period, panelists were given reference standards daily that represented the predominant flavors and textures of the cookies. We trained the panelists using the standards for chewiness and gumminess (*8*). During training, panelists were also given cookies with low, moderate, and high levels of C-trim20 that represented various levels of the flavor and texture attributes. Panel members were given all sample designs during three testing days with each day considered a replicate. The flavors (cereal/grain, sweet, cardboard, bitter, oily) and textures (chewiness, cohesiveness, density, moistness) of cookies were rated on a 0−10 intensity scale. The score sheet with scoring scales for flavor and texture descriptors is shown in **Figure 1**.

For statistical analysis of the physical, textural, and sensory results, a completely randomized design was utilized to determine the significant differences among samples from analysis of variance (ANOVA), and also Duncan's multiple-range test was carried out for mean comparisons.

Name: Date:

Cookie Flavor

Cereal/Grain	0	1	2	3	4	5	6	7	8	9	10
	none		weak			moderate			strong		
Sweet	0	1	2	3	4	5	6	7	8	9	10
	none		weak			moderate			strong		
Cardboard	0	1	2	3	4	5	6	7	8	9	10
	none		weak			moderate			strong		
Bitter	0	1	2	3	4	5	6	7	8	9	10
	none		weak			moderate			strong		
Oily	0	1	2	3	4	5	6	7	8	9	10
	none		weak			moderate			strong		

Cookie Texture

Cohesiveness	0	1	2	3	4	5	6	7	8	9	10
		crumbly								gummy	
Density	0	1	2	3	4	5	6	7	8	9	10
		light								compact	
Moistness	0	1	2	3	4	5	6	7	8	9	10
		dry								moist	
Chewiness	0	1	2	3	4	5	6	7	8	9	10
		tender								tough	

Figure 1. Scoring scales for sensory evaluation for cookies.

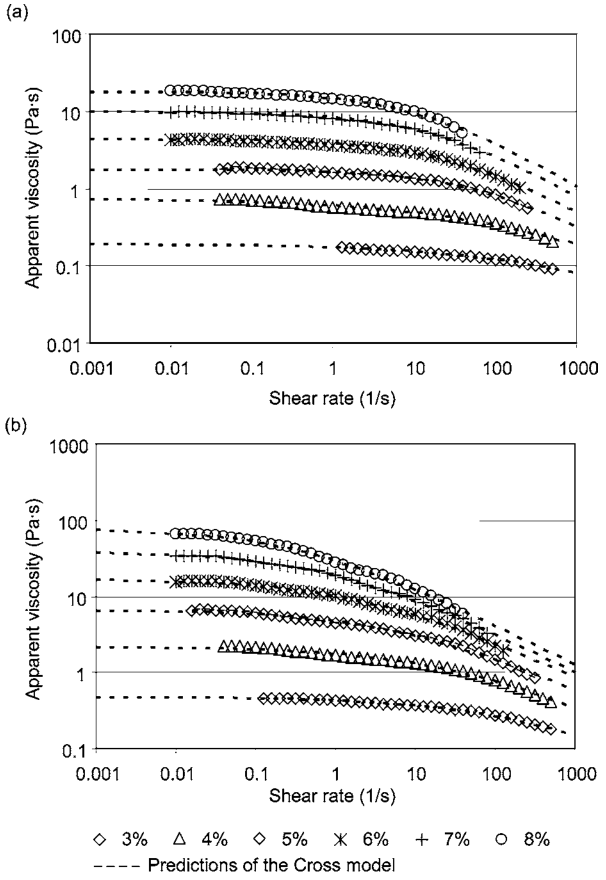

Figure 2. Apparent viscosity versus shear rate plots of C-trim20 (**a**) and C-trim30 (**b**) at different concentrations.

RESULTS AND DISCUSSION

Rheological Characterization of C-trim20 and C-trim30. The apparent viscosities of two oat hydrocolloidal suspensions at different concentrations are shown in **Figure 2**. They exhibited a Newtonian plateau at low shear rates, followed by a rapid decrease in the viscosities at high shear rates. This type of shear-thinning behavior is usual for random coil polysaccharides and has been reported in the literature (*9*−*11*).

Each flow curve was characterized by the Cross equation, which has been widely used to describe the shear-thinning behavior of various polysaccharides (*12*, *13*): $\eta = \eta_\infty + [(\eta_0 - \eta_\infty)]/[(1 + (\lambda\dot{\gamma}^n)]$, where η is apparent viscosity, η_∞ is infinite

Table 1. Magnitude of the Cross-Model Parameters of C-trim20 and C-trim30 Hydrocolloids

	concentration					
	3%	4%	5%	6%	7%	8%
			C-trim20			
η_0	0.192	0.725	1.785	4.329	9.816	17.880
λ	0.002	0.014	0.014	0.032	0.056	0.085
n	0.376	0.384	0.583	0.593	0.606	0.621
R^2	0.997	0.978	0.987	0.990	0.991	0.990
			C-trim30			
η_0	0.478	2.168	6.692	16.980	38.615	79.595
λ	0.006	0.039	0.150	0.445	1.187	2.886
n	0.436	0.453	0.468	0.480	0.510	0.516
R^2	0.995	0.980	0.985	0.995	0.998	0.998

shear rate viscosity, η_0 is zero shear rate viscosity, and λ and n are constants. In this study, it was simplified to $\eta = \eta_0/[(1 + (\lambda\dot{\gamma})^n)]$, assuming $\eta_\infty \approx 0$.

As shown in **Figure 2**, the flow curves of C-trim20 and C-trim30 suspensions were satisfactorily fitted to the Cross model. **Table 1** reports Cross parameters obtained at several different concentrations. The increase in the zero shear rate viscosity was observed in both samples with increasing concentrations as expected. With enhancing concentration, individual random coils in a polymer solution start to overlap and interpenetrate one another (*10*). It leads to the formation of entanglements, consequently causing the viscosity to increase. C-trim30 created more viscosity than C-trim20 at the same concentration. The high β-glucan content of C-trim30 would probably contribute to its high viscosity. The structural relaxation time (λ) is involved in the transition from Newtonian to shear-thinning behaviors. An increase in λ with concentration is shown in **Table 1**. High concentration restricts the motion of polymer chains in a system, retarding the formation rate of new entanglements (*13*). Therefore, the Newtonian flow limit was shifted to lower shear rates with an increase in concentration. The value of n, which is a dimensionless power index for the Cross equation, indicates the degree of shear-thinning behaviors. It approaches zero for Newtonian fluids, whereas shear-thinning materials have a positive n mostly below unity. For both samples, an increase in concentration was accompanied with an increase in n, indicating that shear-thinning behaviors became more apparent at high concentrations.

Shear-thinning behavior of a material has several potential advantages in food applications. Because viscosity is reduced at shear rates, it becomes favorable in industrial operations such as mixing and pumping. In addition, it is reported that the polysaccharide solutions in which viscosity decreases rapidly at shear rates are easily and quickly swallowed (*14*). Hence, the shear-thinning behavior can impart a light and nonslimy mouthfeel to food products.

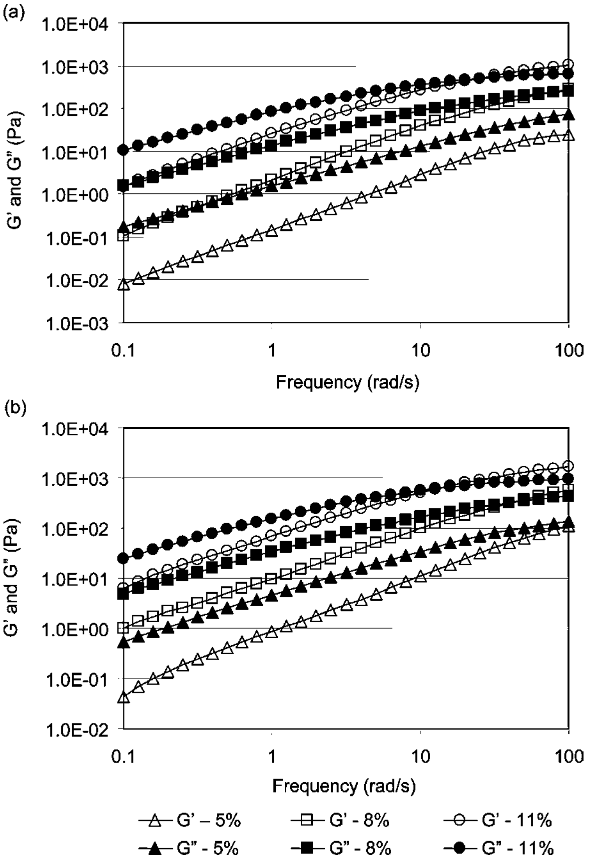

Figure 3. Dynamic viscoelastic spectra of C-trim20 (**a**) and C-trim30 (**b**) at concentrations of 5, 8, and 11%.

Table 2. Physical Properties of Cookies in Which Flour Was Replaced with C-trim20 at Levels of 0, 10, 20, and 30%[a]

	control	10% C-trim20	20% C-trim20	30% C-trim20
diameter (cm)	7.98a	7.58b	7.05c	6.71d
height (cm)	0.87d	0.97c	1.09b	1.19a
moisture content (%)	3.72d	5.33c	6.66b	8.36a
water activity	0.28d	0.38c	0.47b	0.56a

[a] Measurements were made in triplicate, and means with the same letter in the same row are not significantly different at the 1% level.

Figure 3 shows the storage (G') and loss (G'') moduli of C-trim20 and C-trim30 hydrocolloidal suspensions against frequency. Two samples exhibited similar viscoelastic profiles over concentrations. At low frequency, G'' was greater than G', showing liquid-like behavior. As frequency increased, both moduli increased with more frequency dependence of the G', causing the crossover of the G' and G'' curves. At low frequency, molecular chains are allowed to disentangle and rearrange during long periods of oscillation, whereas they cannot disentangle during short periods of oscillation at high frequency. Thus, G' becomes greater than G'' at high frequency because the entanglements act like temporary cross-links (*15*). The onset of the elastic zone where G' dominates over G'' was shifted progressively toward lower frequency with increasing concentration due to elevated entanglements. This viscoelastic behavior is typical of non-interacting polymers with topological entanglements and has been observed in many polysaccharides (*16*, *17*). Therefore, these two oat hydrocolloids can be categorized as an entangled network rather than a cross-linked network gel.

Evaluation of C-trim20 in Cookie Baking. Table 2 presents the dimensions of cookie samples measured, indicating the effect of C-trim20 on the spreading characteristics of cookies. The results show that the control cookies had the greatest diameter and the least height, implying the greatest spread. Flour replacement with C-trim20 caused, however, significant reduction in diameter and increase in height of cookies ($p < 0.01$). Cookie doughs expand both radially and vertically during baking, followed by collapse. This leads to the dramatic increase in cookie diameter after baking. It is mainly due to the property of soft wheat flour, which is extensible film formation due to the lack of elastic properties (*18*). Therefore, the diameter decreases of C-trim20 cookies might be related to the contribution of the C-trim20 to the elastic properties of cookie doughs.

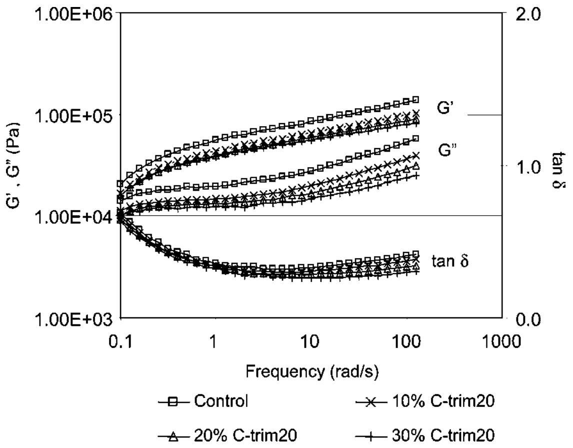

Figure 4. Effect of flour replacement with C-trim20 on the viscoelastic properties of cookie dough.

The moisture content and water activity of cookie samples are also presented in **Table 2**. Although the control had the lowest water content, increasing levels of C-trim20 produced cookies with high water content. The same trend was observed in the water activity of the cookies, which plays an important role in storage stability of foods. Cookies prepared with C-trim20 in this study had the water activity range of 0.35–0.58, which was below the limit of microbial proliferation (*19*).

The effect of C-trim20 on the dynamic viscoelastic properties of cookie dough was investigated. It is shown in **Figure 4** that both moduli (G' and G'') of all samples increased with increasing frequencies, showing frequency dependence. Moreover, G' was significantly higher than G''. This implies obviously that cookie dough has more solid-like behaviors. Cookie dough is characteristic of low moisture and high fat and sugar, leading to no gluten development in a dough. It is therefore recognized that cookie dough has barely cohesive properties under tension (*20*). In addition, previous studies on the viscoelastic properties of cookie (*21*) and biscuit doughs (*22*, *23*) reported higher storage moduli than loss moduli, which could be favorably compared with our results. More pronounced differences were observed between the control and C-trim20 cookie doughs. The control had the highest values of both storage and loss moduli, which decreased in the cookie doughs containing C-trim20. This reduction of the dynamic moduli would be associated with more water content in the C-trim20 cookie doughs because water has strong plasticizing effects (*24*). In addition, it is worth noting the change in tan δ, which is another popular way to indicate relative viscous and elastic properties of a material. The results show that flour replacement with C-trim20 gave rise to the reduction of tan δ in cookie doughs, which was more distinct at high frequencies. Because it is well recognized that water does not affect tan δ (*22*, *24*), the change in the tan δ would be probably due to C-trim20, modifying the structure of cookie doughs.

Changes in the rheological properties of cookie doughs upon heating were also compared. **Figure 5** shows the storage moduli and tan δ of each sample, which have similar heating profiles among the samples. Typically, the abrupt reduction in G' was observed during initial heating (~50 °C), and then the G' remained almost constant (~90 °C). The initial decrease in the G' would be mainly due to shortening melting, which made cookie dough viscous. Interesting results were, however, observed in cookie samples containing C-trim20. During heating, they exhibited higher G' and lower tan δ than the control. This clearly shows that flour replacement of C-trim20 elevated the elastic properties of cookie dough, compared to the control. Consequently, the reduced expansion of C-trim20 cookies shown in **Table 2** could be explained by their enhanced elastic properties.

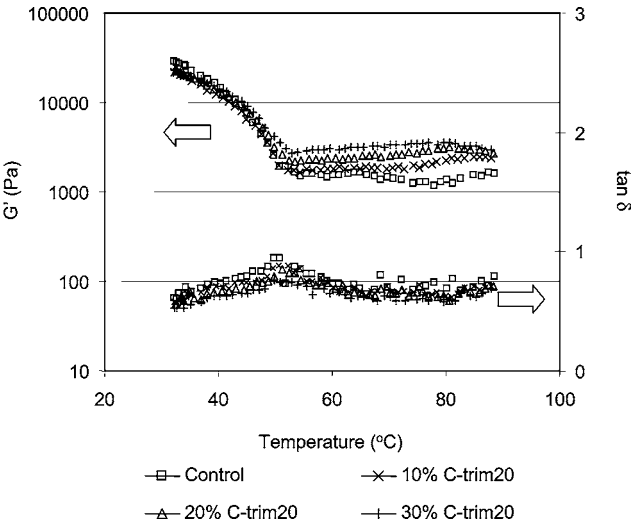

Figure 5. Changes in the dynamic viscoelastic properties of cookie dough over temperature.

Table 3. Effect of Flour Replacement with C-trim20 on the Texture of Cookies[a]

	hardness (N)	peak distance (mm)
control	30.3a	0.87c
10% C-trim20	30.5a	0.70c
20% C-trim20	23.2b	2.03b
30% C-trim20	12.8c	3.96a

[a] Measurements were made in triplicate, and means with the same letter in the same column are not significantly different at the 1% level.

The textural properties of cookie samples were studied by using probing tests. **Table 3** shows that no significant differences between the control and 10% C-trim20 cookies were observed in the maximum peak force, which represents the maximum resistance of cookies when they break and has been reported as hardness or firmness (*18*). However, more flour replacement with C-trim20 produced cookies with less hardness than the control and 10% C-trim20 cookies. Also, the peak distances of each sample are given in **Table 3**, which indicate the compressibility or brittleness of cookies. Compared to the control, there was no change in the peak distance of 10% C-trim20 cookies, whereas 20 and 30% C-trim20 cookies became more compressible and less brittle. This would be explained mainly by increased moisture content.

Sensory properties of cookies were investigated and are shown in **Table 4**. Overall, the attributes of cereal/grain and cardboard increased with increasing amounts of C-trim20, whereas the intensity of the sweet attribute decreased. Only the cookies in which 30% flour was replaced with C-trim20 had significantly more cereal/grain flavor than the control. Cookies made with 10 and 20% C-trim20 were as sweet as the control cookies. Also, incorporation of C-trim20 up to 15% produced cookies with similar cardboard flavor to the control. No significant differences were observed in bitter and oily flavors. Also, **Table 4** reports the texture attributes for the cookies. The attributes of chewiness, cohesiveness, density, and moistness increased with increasing flour substitution by C-trim20. The control was significantly less chewy than the cookies made with 15 and 25% C-trim20. The cookies containing 10% C-trim20 had more similar cohesiveness to the control than any of the

Table 4. Sensory Evaluation of Cookies Prepared with C-trim20[a,b]

	control	flour replacement with C-trim20 10%	15%	20%	25%	30%
Flavor/Taste						
cereal/grain	2.4b	2.8b	3.0ab	3.3ab	2.9b	3.8a
sweet	3.6a	3.2ab	2.7bc	3.1ab	1.9cd	1.6d
cardboard	0.9d	1.0cd	1.1bcd	1.9abc	2.1ab	2.6a
bitter	0.3	0.4	0.3	0.4	0.4	0.3
oily	0.2	0.4	0.4	0.4	0.4	0.4
Texture						
chewiness	2.8b	3.3ab	4.3a	3.9ab	4.3a	3.7ab
cohesiveness	1.7d	1.9cd	2.8c	3.9b	5.7a	4.8ab
density	3.0c	3.4c	4.1bc	4.5b	6.1a	4.8b
moistness	1.5d	1.4d	2.8c	3.7bc	5.3a	4.6ab

[a] Sensory analysis was conducted in triplicate by a 15 member trained panel. [b] Means with the same letter in the same row are not significantly different at the 5% level. No letter indicates no significant differences between the sample ratings.

other cookies. Compared to the control, no significant differences in density and moistness were observed in the cookies at 15 and 10% levels of flour replacement with C-trim20, respectively. Consequently, the cookies in which flour was replaced with C-trim20 up to 10% demonstrated sensory properties similar to those of the control. Hence, the sensory evaluation was in great agreement with measurements derived from the texture analyzer.

Because C-trim20 and C-trim30 do not display gelling properties, they can be used as a highly viscous thickener, controlling the texture and rheology of foods. Furthermore, they can improve nutrition beyond the typical use of hydrocolloids. Due to high levels of natural β-glucan, they can contribute to the content of dietary fibers, making it possible to claim a health benefit and “natural” statement on food labels. Thus, these hydrocolloids may be advantageously used in developing potential healthy and nutritional food products without losing desirable qualities.

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