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Influence of water and barley β-glucan addition on wheat dough viscoelasticity

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ABSTRACT

The effects of the addition of two barley β-glucan isolates (0.2–1.0% of wheat flour), differing in molecular weight, and water (53–63% in a poor breadmaking wheat flour, cv. Dion, and 58–68% in a good breadmaking wheat flour, cv. Yekora) on the viscoelastic properties of wheat flour doughs were investigated. A response surface model (CCF) was used to evaluate the effects observed on the dynamic and creep-recovery parameters of the dough. The evaluation was done separately for each combination of β-glucan isolate (BG1 of ~10^5 Da and BG2 of ~2×10^5 Da) and flour type. Besides the contents of β-glucan and water, the molecular size of the polysaccharide and the flour quality were important determinants of the dough's viscoelastic behavior. Compared to BG1, the higher molecular weight β-glucan (BG2) brought about major changes on all the rheological responses of the fortified doughs. The addition of appropriate levels of β-glucans and water in the poor breadmaking cultivar (Dion) doughs could yield similar viscoelastic responses to those observed by a non-fortified good breadmaking quality flour dough (Yekora).

1. Introduction

Consumer concerns regarding healthy diets and convenience foods have significantly increased in the last decade. Nowadays, consumers are interested in the quality, nutritive value and safety of the products they eat. Cereal non-starch polysaccharides are considered as food ingredients with a significant impact on human health. The beneficial health effects of β-glucans, one of the major non-starch polysaccharides of cereal grains, include both serum cholesterol lowering and the insulin and glucose-attenuating effects (Behall, Scholfield, & Hallfrisch, 2004; Cavallero, Empilli, Brighenti, & Stanca, 2002; Kerckhoffs, Hornstra, & Mensink, 2003; Wang, Newman, Newman, & Hofer, 1992). The physiological improvements induced by β-glucans have been related to the ability of these polysaccharides to increase intestinal viscosity (Wood, Weisz, & Blackwell, 1994). Two important factors among others that influence the viscosity of β-glucans are molecular weight and concentration of these polysaccharides (Lazaridou, Biliaderis, & Izydorczyk, 2003; Skendi, Biliaderis, Lazaridou, & Izydorczyk, 2003; Vaikousi, Biliaderis, & Izydorczyk, 2004; Wood, Weisz, & Blackwell, 1991).

The potential use of β-glucans as fibre-enriching agents in breadmaking, mainly in the form of flour fractions that are isolated from various cereals, has been reported by different authors (Cavallero et al., 2002; Chaudhary & Weber, 1990; Izydorczyk, Hussain, & MacGregor, 2001; Knuckles, Hudson, Chiu, & Sayre, 1997). A major difficulty when dealing with flour fractions rich in β-glucans is their detrimental effect on the dough handling properties and the volume and the color of the fortified bread (Dhingra & Jood, 2004; Knuckles et al., 1997). These disadvantages together with the health benefits present a major challenge for the food scientists to produce β-glucan-enriched breads of comparable quality to white breads.

Many authors have reported that due to the β-glucans ability to absorb high quantities of water, doughs fortified with β-glucans display a significant increase in the farinograph water absorption values (Cavallero et al., 2002; Knuckles et al., 1997; Skendi, Biliaderis, Papageorgiou, & Izydorczyk, 2009; Skendi, Papageorgiou, & Biliaderis, 2009). It is generally recognized that water plays the most important role on the viscoelastic properties of the dough during mixing; i.e. the distribution of the dough materials, their hydration, and the gluten protein network development strongly depend on the quantity of added water.

Small deformation dynamic rheological tests and creep-recovery measurements are often employed for dough characterization and the derived rheological data are explored as predictors of breadmaking performance (Collar & Bollain, 2004; Edwards, Dexter, Scanlon, & Cenkowski, 1999; Edwards, Peressini, Dexter, & Mulvaney, 2001; Safari-Ardi & Phan-Thien, 1998). A previous study on the rheological behavior of β-glucan-enriched doughs prepared to achieve a maximum consistency of 500 BU (Brabender Units) has revealed the importance of flour quality, concentration and molecular size of the polysaccharide added (Skendi, Papageorgiou et al., 2009). In all previous works on breadmaking of fortified wheat doughs emphasis has been placed on the effect of added

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polysaccharides, either as single ingredients or in combination with other hydrocolloids and improvers, on dough and bread characteristics. In this context, and taking into account the important role of water, the investigation of the combined effects of β-glucans and water could provide a more thorough view on the changes that the polysaccharide and water can bring into the viscoelastic properties of the fortified doughs. A useful tool, widely employed to evaluate the effect of additives or processing parameters on dough properties and bread quality, is the response surface methodology (Collar, Andreu, Martinez, & Armero, 1999; Gallagher, O'Brien, Scannell, & Arendt, 2003; Junqueira et al., 2007; Rosell, Santos, & Collar, 2006).

The objective of the present study was to evaluate the combined effects of water and polysaccharide addition on the dough viscoelastic properties, using large and small deformation mechanical testing, and to explore the possibility of improving the dough handling behavior in addition to the nutritional value of product. A thorough study of the viscoelastic responses of polysaccharide-fortified doughs can provide information on how the effects of adding β-glucans in the hydrated gluten network matrix are balanced by water addition.

2. Materials and methods

2.1. Flour preparation and β-glucan isolation

Seeds of two Greek wheat (*Triticum aestivum*) cultivars, differing in their breadmaking quality, and two Greek barley cultivars (Persefoni and Kos), used as a source of the β-glucan isolate, named BG2, were provided by the National Agricultural Research Foundation, Cereal Research Institute, Thessaloniki, Greece. A barley β-glucan concentrate provided by CEBA (Lund, Sweden) was used to obtain the BG1 isolate. Wheat seeds from the poor breadmaking quality cultivar Dion, and those from the good breadmaking quality Yekora, were cleaned from impurities and tempered to 14.5% (in a dry basis) moisture before milled on a Brabender Quadromat Senior (Brabender, Duisburg, Germany). The quality characteristics of the flours were determined with AACC (2000) official methods, 46-13 (1986) and 08-01 (1983) for protein and ash content, and with ICC-Standards (1994) No. 110/1 (1976) and No. 155 (1994) for moisture content and gluten index, respectively. The extraction procedure followed to obtain the BG1 and BG2 β-glucan isolates, with respective molecular weights of 10^5 and 2×10^5, is described in detail elsewhere (Skendi, Papageorgiou et al., 2009). The protein content and DP_3/DP_4 (cellotriosyl/cellotetraosyl) ratios of the two isolates were 0.5%, and 2.6% for the BG1 isolate, and 5% and 2.1% for the BG2 isolate, respectively. The molecular size, the DP3/DP4 ratio and the protein level were analyzed according to procedures described elsewhere (Skendi et al., 2003). The β-glucan content of the BG1 and BG2 isolates was 84.5% and 81.3%, respectively, as determined by the McCleary and Glennie-Holmes (1985) method, using the Megazyme® mixed linkage β-glucan assay kit

2.2. Dough preparation for rheological testing

The β-glucan-free doughs were obtained by mixing the flour in a 10 g Farinograph bowl (Brabender, Duisburg, Germany) with distilled water at three levels, as shown in Table 1. Control doughs were also prepared to reach a maximum consistency of 500 BU (Brabender Units) in the farinograph (i.e. 56% for Dion and 60% for Yekora flour). The levels of added polysaccharide isolate (% of wheat flour) and water were chosen from preliminary experiments in order the fortified flour, with the respective quantities of β-glucan and water (Table 1), to yield under-hydrated and over-hydrated doughs with acceptable consistency that could be easily handled. Concentration levels of water and β-glucans out of the range chosen in this study produced doughs that were difficult to prepare in the farinograph and thereafter handled properly. The β-glucan isolate was added in a dry powder form and mixed very well with the wheat flour in the farinograph bowl prior to water addition. In order to avoid the negative effects induced in the quality of bread from a not-properly developed dough (Paredes-Lopez & Bushuk, 1983), all the dough samples were mixed in the farinograph bowl till maximum consistency; i.e. for all dough samples, the same procedure that allows mixing in the farinograph till maximum peak development was adopted. The latter procedure on dough mixing is often used by many authors to characterize dough structures (Lefebvre, 2006; Létang, Piau, & Verdier, 1999).

Table 1
Experimental range and levels of independent coded variables.

Independent variable	Factor	Range and level		
	x_i	−1	0	1
β-Glucan isolate level (% of wheat flour)	x_1	0.2	0.6	1.0
Water added in Dion flour (% farinograph)	x_2	53	58	63
Water added in Yekora flour (% farinograph)	x_2	58	63	68

2.3. Rheological testing

Doughs prepared as described above, were placed in a plastic bag and immediately sealed and allowed to rest for at least 2 h at ambient temperature before any rheological testing. Oscillatory and creep-recovery tests were performed in a Physica MCR 300 (Physica Messtechnic GmbH, Stuttgart, Germany) rheometer equipped with a Paar Physica circulating bath and a controlled peltier system (TEZ 150P/MCR) that was maintained at 25 ± 0.1 °C throughout the experiment. All dough samples were measured using a 25 mm plate–plate geometry (corrugated surfaces to avoid slippage) with a fixed gap of 2 mm. Before each experiment begins the upper plate was moved down at the trim position and then the excess of the dough sample was trimmed out. Application of a wetted cotton layer around the edges of the dough prevented moisture loss for over one hour, without any significant effect on the rheological measurements. After trimming, the sample was allowed to rest for another 20 min in order to allow any built-up residual stresses to decay. The experiment consisted first of one frequency sweep test in the frequency (f) range from 0.1 to 100 Hz, since this measurement caused no changes in the dough structure when carried out at the chosen strain amplitude (0.01%), and subsequently of a creep-recovery test. Preliminary strain sweep tests were used to determine the linear viscoelastic region of the doughs and from these measurements a strain (γ) level of 0.01%, within the linear region, was adopted in all the experiments.

For the creep-recovery tests, during the creep phase the stress was applied for 60 s and then the recovery of the dough was recorded for another 180 s. From preliminary strain sweep tests performed on the β-glucan-enriched doughs two stress (σ) values were chosen to be applied during the creep phase; one beyond the linear region, considered as a high stress level (300 Pa), and the other within the linear viscoelastic region named low stress (50 Pa). At least two replicate dough samples were tested for each dough formulation.

2.4. Experimental design

The response surface model used in this study involved two factors x_1 (β-glucan) and x_2 (water). The central composite face centered (CCF) design contained a total of 13 experiments for the frequency sweep measurements and 10 for the creep-recovery tests, with the first nine experiments organized in a factorial design, while the rest of the experimental trials involved replication of the central point. Repeated observations at the central point were used to estimate the experimental error employed. The ranges and the levels of the coded variables for the wheat flours tested are given in Table 1. The experimental design (Table 2) was replicated twice. The data were analyzed using the MINITAB program (MINITAB, Statistical Software, Release 13.1). The relationships between the measured variables and the two compositional factors (β-glucan and water) were estimated by fitting the data to a second-order polynomial (Eq. (1)) where, Y is the response variable (e.g., storage modulus (G'), loss modulus (G''), complex viscosity (η^*), maximum creep compliance (J_{max}), zero shear viscosity (η_0), and elastic part of the maximum creep compliance (J_e/J_{max})), b_0 is a constant, b_1 and b_2 are the regression coefficients for the linear effects, b_{11} and b_{22} are the quadratic coefficients and b_{12} is the interaction coefficient.

$$Y = b_0 + b_1x_1 + b_2x_2 + b_{11}x_1^2 + b_{22}x_2^2 + b_{12}x_1x_2 \quad (1)$$

The storage modulus, loss modulus and complex viscosity responses, although they were continuously monitored during dynamic rheological testing in the frequency range from 0.1 to 100 Hz, their value at 1 Hz was used as the response variable in the model. Coefficients of determination (R^2) were computed, and the adequacy of models was tested by estimating the lack of fit. A stepwise deletion of non-significant terms was applied. The statistically non-significant linear terms were included in the model when their respective quadratic or interactive terms were statistically significant. In order to determine the effect of the independent variables on the rheological parameters of the dough together with the model, contour plots for each parameter were generated for each combination of the β-glucan isolate and flour type.

Table 2
A CCF design with five replicates of the centre point for sampling.

Run	Coded levels	
	β-Glucan	Water
1	−1	−1
2	1	−1
3	−1	1
4	1	1
5	−1	0
6	1	0
7	0	−1
8	0	1
9	0	0
10	0	0
11	0	0
12	0	0
13	0	0

3. Results and discussion

The flour quality data showed that the Dion flour had 12.4% protein, 0.48% ash, 10.7% moisture content and a gluten index of 26.2%, whereas for the Yekora flour the corresponding values were 17.0%, 0.64%, 10.7% and 67.2%, respectively. The impact of both β-glucan and water addition on dynamic oscillatory and creep-recovery parameters of the dough and the consequent constitutive modeling of the viscoelastic behavior of the dough have been investigated. Coefficients of the variables of the models, R^2 and $R^2_{(adj)}$, and a test for the lack of fit used to evaluate the adequacy of the models, were computed for each combination of flour type and the β-glucan isolate, and the results are shown in Tables 3–5. In addition, comparisons of dough viscoselastic parameters with that of the control were made to evaluate how the β-glucan effects can be balanced by water addition and how the combination of both factors could yield the viscoelastic properties of the non-fortified dough sample of the good breadmaking quality wheat cultivar.

3.1. Effect on dynamic rheological properties of dough

Dynamic oscillatory tests have been previously employed to understand the factors affecting the rheological properties of cereal flour doughs (Amemiya & Menjivar, 1992; Izydorczyk et al., 2001). Khatkar and Schofield (2002), Petrofsky and Hoseney (1995), and Skendi, Papageorgiou et al. (2009) observed that the storage modulus of a poor breadmaking quality flour dough was higher than that of doughs made from a good breadmaking quality flour. In a previous study (Skendi, Papageorgiou et al., 2009) different doughs were compared at the same farinograph consistency (500 BU), but not at the same water content. Indeed, the control dough (no added β-glucan) from the Dion flour, prepared to reach a consistency of 500 BU with 56% added water, exhibited higher storage and loss moduli than the Yekora control dough with 60% added water, indicating that the poor breadmaking quality flour yielded a much stiffer dough (Fig. 1). The data of Fig. 1 also indicate that if instead the

Table 3
Estimated regression coefficients and statistical parameters of models for dynamic rheological characteristics from β-glucan-enriched Dion and Yekora dough samples (analysis was done using uncoded units).

Factors[a]	Dion BG1			Dion BG2			Yekora BG1			Yekora BG2		
	G' (Pa)	G'' (Pa)	η^* (Pa s)	G' (Pa)	G'' (Pa)	η^* (Pa s)	G' (Pa)	G'' (Pa)	η^* (Pa s)	G' (Pa)	G'' (Pa)	η^* (Pa s)
Constant	342,787***	138,342***	59,056***	608,478***	194,675***	94,327***	369,414***	123,856***	71,735***	762,945***	207,233***	124,580***
X_1	−22,338**	−8632**	−3818**	−42,762**	−16,479***	−6468**	8642**	4647***	1350***	23,049***	5457***	3894***
X_2	−10,840***	−4335***	−1865***	−19,376***	−6078***	−2993***	−10,790***	−3568***	−2109***	−22,427***	−6005***	−3657***
X_1^2	−7046***	−2578***	−1196***	12,720***	6755***	2567***	−7286**	−3577***	−1167***	−16,872***	−4032**	−2843***
X_2^2	86***	34***	15***	156***	48***	24***	80***	26***	16***	165***	44***	27***
X_1X_2	551***	210***	94***	579**	175**	77*	–	–	–	–	–	–
R^2 (%)	94.8	95.4	94.9	96.3	97.7	96.8	95.3	96.1	97.7	96.7	96.2	96.4
$R^2_{(adj)}$ (%)	93.4	94.3	93.7	95.3	97.1	96.0	94.4	95.4	97.2	96.0	95.4	95.7
F	72.3	83.1	75.1	102.7	167.5	121.4	107.3	129.7	221.2	152.5	132.1	140.1
Lack of fit	0.612	0.711	0.615	0.064	0.706	0.648	0.141	0.711	0.213	0.345	0.225	0.325

[a] X_1 – β-glucan ; X_2 – water.
* $P \leqslant 0.05$.
** $P \leqslant 0.01$.
*** $P \leqslant 0.001$.

Table 4
Estimated regression coefficients and statistical parameters of models for creep-recovery properties from β-glucan-enriched Dion dough samples (analysis was done using uncoded units).

Factors[a]	Dion BG1 at 50 Pa			Dion BG2 at 50 Pa			Dion BG1 at 300 Pa			Dion BG2 at 300 Pa		
	J_{max}	η_0	J_e/J_{max}	J_{max}	η_0	J_e/J_{max}	J_{max}	η_0	J_e/J_{max}	J_{max}	η_0	J_e/J_{max}
Constant	-3008^{***}	6204^{***}	134^{***}	-8305^{***}	1012^{***}	208^{***}	$-382{,}321^{***}$	556^{***}	818^{***}	$-31{,}393^{***}$	2125^{***}	2120^{***}
X_1	2388^{***}	-247^{*}	-67^{**}	331^{*}	-2090^{***}	-157^{***}	$-14{,}347^{***}$	17^{***}	36^{***}	$30{,}449^{***}$	-63^{*}	-359^{***}
X_2	61^{***}	-202^{***}	-1^{***}	283^{***}	-12^{***}	-3^{***}	$13{,}143^{***}$	-19^{***}	-28^{***}	604^{***}	-71^{***}	-68^{***}
X_1^2	656^{***}	-185^{***}	-24^{***}	-307^{**}	896^{***}	-29^{*}	$-10{,}542^{***}$	-12^{**}	-26^{***}	1419^{**}	94^{***}	60^{***}
X_2^2	–	2^{***}	–	-2^{***}	–	–	-110^{***}	0.2^{***}	0.2^{***}	–	1^{***}	1^{***}
X_1X_2	-58^{***}	8^{***}	2^{***}	–	–	3^{***}	–	–	–	-608^{***}	–	6
R^2 (%)	93.2	97.1	81.5	74.0	96.6	80.3	94.4	92.4	89.4	99.4	90.4	97.4
$R^2_{(adj)}$ (%)	91.3	96.1	76.5	67.1	95.7	75.1	93.0	90.4	86.5	99.2	87.8	96.4
F	51.1	94.1	16.5	10.7	106.5	15.3	63.8	45.7	31.5	598.8	35.2	103.0
Lack of fit	0.109	0.078	0.449	0.09	0.134	0.056	0.055	0.069	0.09	0.076	0.093	0.024

[a] X_1 – β-glucan ; X_2 – water.
[*] $P \leqslant 0.05$.
[**] $P \leqslant 0.01$.
[***] $P \leqslant 0.001$.

Table 5
Estimated regression coefficients and statistical parameters of models for creep-recovery properties from β-glucan-enriched Yekora dough samples (analysis was done using uncoded units).

Factors[a]	Yekora BG1 at 50 Pa			Yekora BG2 at 50 Pa			Yekora BG1 at 300 Pa			Yekora BG2 at 300 Pa		
	J_{max}	η_0	J_e/J_{max}	J_{max}	η_0	J_e/J_{max}	J_{max}	η_0	J_e/J_{max}	J_{max}	η_0	J_e/J_{max}
Constant	7059^{*}	3875^{**}	-461^{*}	-228^{***}	$27{,}715^{***}$	157^{***}	-4255^{***}	244^{***}	131^{***}	-1532^{***}	$13{,}399^{***}$	168^{***}
X_1	-1875^{***}	726^{***}	69^{*}	-79^{***}	3100^{***}	7^{***}	3630^{**}	90^{***}	8^{**}	-142^{***}	3634^{***}	-73^{*}
x_2	-227^{**}	-102^{*}	17^{**}	5^{***}	-836^{***}	-1^{***}	77^{***}	-4^{***}	-1^{***}	28^{***}	-418^{***}	-2^{***}
X_1^2	233^{*}	-631^{***}	–	53^{**}	-776^{***}	–	–	-65^{**}	–	–	-214^{*}	-16^{*}
X_2^2	2^{**}	1^{*}	-0.1^{**}	–	6^{***}	–	–	–	–	–	3^{***}	–
x_1x_2	27^{***}	–	-1^{**}	–	-31^{*}	–	-62^{**}	–	–	–	-50^{***}	2^{**}
R^2 (%)	93.9	97.9	81.7	93.4	96.4	90.5	82.4	89.5	79.9	92.3	98.6	86.3
$R^2_{(adj)}$ (%)	91.7	97.3	76.8	92.1	95.1	89.4	79.1	87.5	77.5	91.4	98.1	82.7
F	43.0	173.0	16.7	75.3	75.3	80.7	25.0	45.3	33.8	101.5	192.3	23.7
Lack of fit	0.683	0.169	0.097	0.636	0.174	0.251	0.211	0.085	0.422	0.063	0.128	0.479

[a] X_1 – β-glucan; X_2 – water.
[*] $P \leqslant 0.05$.
[**] $P \leqslant 0.01$.
[***] $P \leqslant 0.001$.

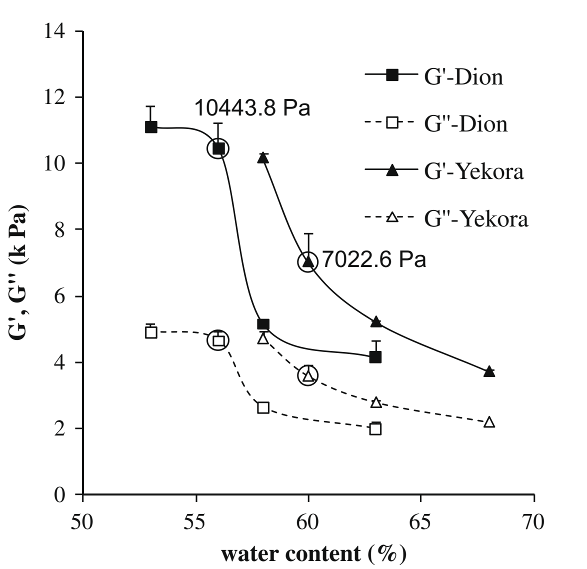

Fig. 1. Influence of the water content on storage (G') and loss (G'') moduli of β-glucan-free Dion and Yekora dough samples measured at 25 °C; the circled data points refer to the respective dough samples with a consistency of 500 BU.

same water concentration is used for both types of flour, the dough of the good breadmaking quality flour exhibits higher G' and G'' values than the dough made from the poor breadmaking quality flour. This behavior can be expected since the good breadmaking quality wheat flour has the ability to form a stronger and a more organized gluten network due to its higher content of gluten proteins. Based on these observations, it is important to take into account the quantity of water added during dough development when comparing dynamic oscillatory parameters of the dough.

There is a general consensus that as water content of the dough increases, within a given flour dough system, both the elastic (G') and the viscous moduli (G'') decrease (Amemiya & Menjivar, 1992; Faubion & Hoseney, 1990; Navickis, Anderson, Bagley, & Jasberg, 1982). In accordance with this view, both G' and G'' of the control (free of β-glucan) Dion and Yekora doughs decreased with increased level of water (Fig. 1); the decrease observed in the G' was more pronounced than in the G''. In the same context, Létang et al. (1999) observed a change in the slope of the maximum dough consistency curve above a certain water level due to the presence of excess free water.

The data in Table 3 reveal that the developed model equations described adequately the responses of storage modulus, loss modulus and complex viscosity within the adopted range of the two variables examined in this study. The effect of each variable on the above mentioned responses for the Dion doughs is through the combination of coefficients and variable values as well as a contribution of the interaction terms, whereas for Yekora doughs the latter contributions were not significant on the measured responses. The high R^2 values (greater than 94.8%) obtained for Dion flour, are satisfactory, indicating that only 2.3–5.2% of the total variation is not explained by the model. The values of the adjusted R^2 ($R^2_{(adj)}$) were also high (greater than 93.4%), supporting the adequacy of the model to describe the rheological responses as a function of the two variables. High R^2 values and $R^2_{(adj)}$ were also obtained for the Yekora doughs (Table 3); typical R^2 were greater than 95.3% and $R^2_{(adj)}$ greater than 94.4%.

The contour plots for the G' of all β-glucan-enriched doughs are shown in Fig. 2. Generally, for all the parameters of the dynamic oscillatory measurements, i.e. G', G'' and η^*, of β-glucan-enriched doughs, significant linear and quadratic effects for both factors (water and β-glucan) were observed. When the water content increased, the G' values of all β-glucan-enriched doughs decreased (Fig. 2a–d). Similar observations were also made by Phan-Thien and Safari-Ardi (1998). For Dion β-glucan-enriched doughs, the water quantity needed in order to reach the G' value of the control Yekora dough (7022.6 Pa) increased with increasing the BG1 content, reached a maximum around 0.75% and after that it decreased (Fig. 2a). Similarly, Fig. 2b shows a continuous increase of the required water when the BG2 isolate is increased till 0.7% in order to reach the G' values of the Yekora control dough; further increase of the BG2 concentration resulted in dough structure with G' greater than that of the control Yekora dough. Overall, the effect of the BG2 isolate was greater than that exhibited by its lower molecular weight counterpart.

The addition of β-glucans increased the G' values of the good breadmaking quality flour at 60% water, a level that corresponds to the water needed to prepare the Yekora control dough in the farinograph (500 BU); the BG2 isolate was more effective in increasing the G' values (Fig. 2c and d). For the Yekora flour, the pattern observed in the G' values of the BG1-enriched doughs was similar to that of the doughs fortified with the BG2 preparation (Table 3 and Fig. 2c and d).

The loss modulus (G'') and complex viscosity (η^*) behaved similarly to the storage modulus (G') (Table 3). The observed significant interactions between the two factors in all dynamic rheological parameters of the Dion doughs indicated that the influence of the β-glucans was dependent on the level of added water (Table 3). Furthermore, several combinations of added β-glucans and water in the poor breadmaking quality flour could result in responses similar to that of the good breadmaking quality flour (control dough). Considering both factors, the water content was clearly the most predominant in influencing the dough dynamic oscillatory rheological properties.

3.2. Effect on creep-recovery rheological properties of dough

The viscoelastic properties of wheat doughs varying in β-glucan and water contents were also analyzed by creep-recovery tests. The creep-recovery results are described in terms of creep compliance, $J(t)$, and fitted to a Burgers model for the creep (Eq. (2)) and the recovery phases (Eq. (3)) as follows:

$$J(t) = J_0 + J_m(1 - \exp(-t/\lambda)) + t/\eta_0 \quad (2)$$

$$J(t) = J_{max} - J_0 - J_m(1 - \exp(-t/\lambda)) \quad (3)$$

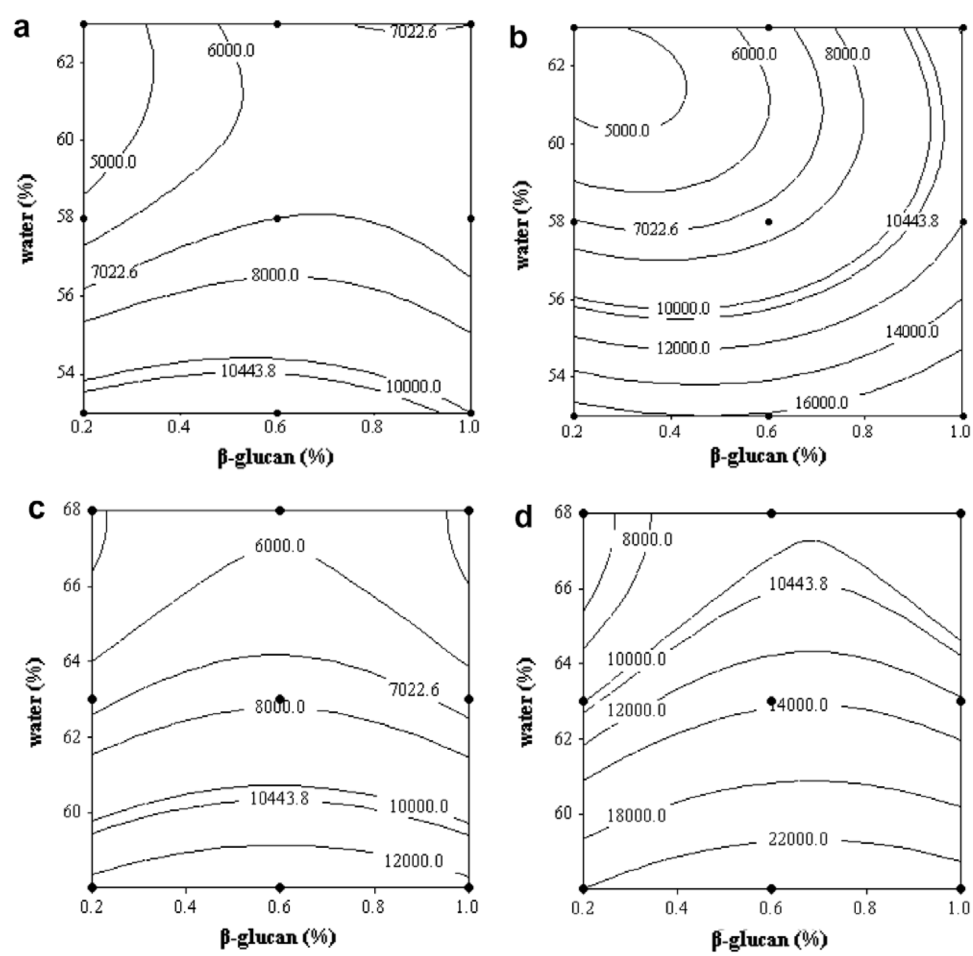

Fig. 2. Contour plots of storage modulus (G'): (a) Dion BG1, (b) Dion BG2, (c) Yekora BG1 and (d) Yekora BG2; the G' values of the control doughs (β-glucan-free doughs with a consistency of 500 BU) are 10443.8 Pa for Dion and 7022.6 Pa for Yekora flour.

where t is the time, J_{max} is the maximum creep compliance, J_0 the instantaneous compliance, J_m the maximum viscoelastic compliance, η_0 is the zero shear viscosity and λ is the mean retardation time. In addition, the remaining deformation after creep stress removal represents the viscous component of the maximum compliance (J_v), whereas the recovered deformation (J_e) represents the elastic component. According to the work of Lefebvre (2006), the analysis of creep tests, as presented by Ferry (1980) for the linear viscoelastic behavior, is still valid above this region provided that the non-Newtonian viscosity does not vary during the time of dough testing; this condition is met when the time of measurement is short as in the present work.

Generally, increasing the water level in the β-glucan-free doughs increased their J_{max} values and decreased the η_0 and J_e/J_{max} values (Fig. 3a and b), regardless of the quality of the flour used or the level of the stress applied. All free of β-glucan Yekora doughs subjected to low or high stress exhibited lower J_{max} and higher η_0 and J_e/J_{max} than the respective Dion free β-glucan doughs prepared with the same water content and subjected to the same stress (Fig. 3a and b). Generally, increasing the water content in the β-glucan-free doughs created less elastic and less resistant to deformation dough structures. Edwards et al. (1999) also observed that increasing water absorption of doughs increased the maximum strain attained during the creep tests performed at large deformation.

The simultaneous effects of water and β-glucan on the creep-recovery parameters of the dough were further explored by response surface methodology. The mathematical models of the creep-recovery parameters were evaluated statistically by analysis of variance. All derived models seemed to predict well the experimental responses ($P < 0.05$). The R^2 and $R^2_{(adj)}$ values are both high, and the R^2 is in agreement with the $R^2_{(adj)}$ for all responses (Tables 4 and 5). The lack of fit of the developed empirical models of the creep-recovery parameters are all >0.05, except for the J_e/J_{max} of BG2-enriched Dion doughs measured under high stress (300 Pa); even in the latter case the R^2 and $R^2_{(adj)}$ were very high (97.4 and 96.4, respectively), suggesting that the applied model explained very well the experimental data. Representative contour plots of the response functions of creep-recovery parameters measured under low (50 Pa) and high (300 Pa) stress are presented in Figs. 4 and 5, respectively.

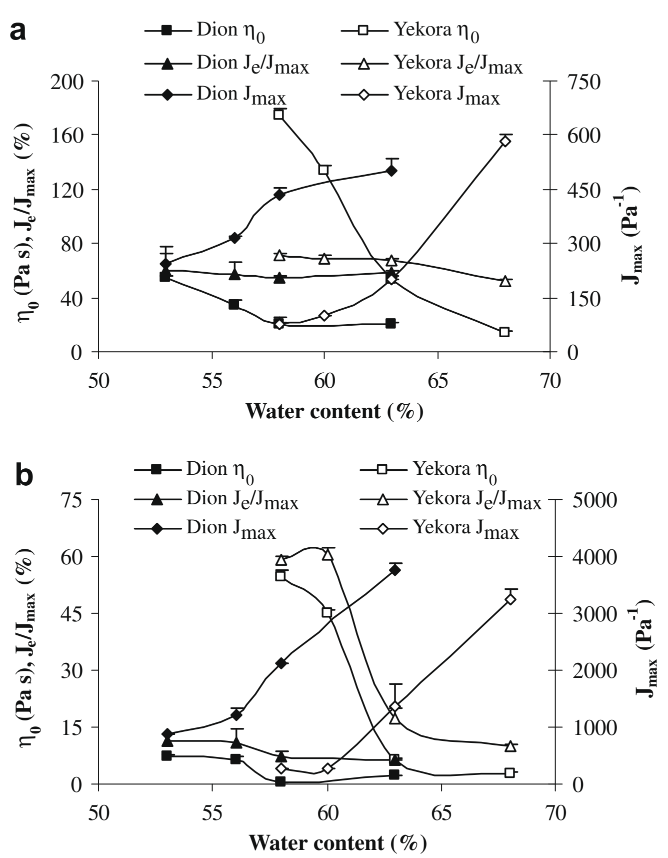

Fig. 3. Influence of water content on the creep-recovery parameters of β-glucan-free doughs from two different breadmaking quality flours (Dion and Yekora) measured under low, 50 Pa, (a) and high levels, 300 Pa, (b) of applied stress.

The effect of BG1 on the J_{max} of Dion doughs measured at 50 Pa stress (J_{max}-50) was greater than that of the water (Table 4). The J_{max}-50 values of the BG1-enriched Dion doughs can be in the range of the control Yekora dough (100.64 Pa^{-1}) when the added water is less than 54.5% in the polysaccharide range of 0.3–0.8% (Fig. 4a). Although the addition of BG1 resulted in an increase of the zero shear viscosity and the elastic part of the J_{max} measured under low stress (η_0-50 and J_e/J_{max}-50, respectively), there was no combination (within the ranges of β-glucan and water used) of the studied variables to result in doughs with η_0-50 and J_e/J_{max}-50 values similar to those of the control Yekora dough (i.e. 134.33 Pa s and 69.04%, respectively) (Table 4 and Fig. 4b).

When the BG2 isolate was added in the Dion flour, the quadratic coefficients of both variables that describe the J_{max}-50 behavior of the fortified dough were negative (Table 4), indicating that the response yields a maximum value (Fig. 4c). Even when the maximum is reached in the response (150 Pa^{-1}), the J_{max}-50 values were lower than 313.65 (Pa^{-1}) of the β-glucan-free control Dion dough. The J_{max} values of the control Yekora (100.64 Pa^{-1}) are reached for polysaccharide concentration less than 0.8% and for a water content less than 56%, whereas for higher BG2 levels a greater amount of water is required (Fig. 4c). The η_0-50 values of the BG2-enriched Dion doughs were much higher than those of the control Dion (33.80 Pa s) in the entire experimental window studied (Table 4) and values similar to that of Yekora control (134.33 Pa s) could be also obtained. In Fig. 4d one can observe that addition of BG2 in Dion doughs generally produced an increase in the elasticity of the doughs (>57.95%), except for the combinations of polysaccharide less than 0.3% and water more than 60%. The J_e/J_{max}-50 values similar to the Yekora control dough (69.04%) were achieved by combining less than 0.7% BG2 with more than 54% water and more than 0.8% polysaccharide with less than 58% water content. Generally, the BG2-enriched Dion doughs were less 'sensitive' against water addition than the respective BG1-fortified doughs. Furthermore, the BG2 was more effective in giving similar values of the studied creep-recovery parameters to those of the Yekora control dough.

The effect of BG1 isolate on the creep-recovery parameters of the Yekora doughs (J_{max}-50, η_0-50, and J_e/J_{max}-50) is shown in Table 5. The BG1 exhibits a curvilinear (concave upward) concentration-related increase in the J_{max}-50. This is reflected by the negative value of the linear coefficient (X_1), causing an initial downward slope, and the positive value of the coefficient for the quadratic term (X_1^2) of J_{max}-50, causing the curvilinearity (upward due to the positive sign). The BG1 causes a linear increase in J_e/J_{max}-50, generated by the positive value of the linear (X_1) coefficient which causes an upward slope. The quadratic term (X_1^2), since it was not found to be statistically significant is not included in the model. On the other hand, the water exhibits a curvilinear (concave downward) concentration-related increase in the J_e/J_{max}-50 because of the positive sign of the coefficient of the linear term and the negative value of the quadratic term in the model. The shapes of the J_{max}-50 and J_e/J_{max}-50 are explained on the basis of the respective significant coefficients of the models which imply that at high BG1 concentration less water is required in order to achieve the

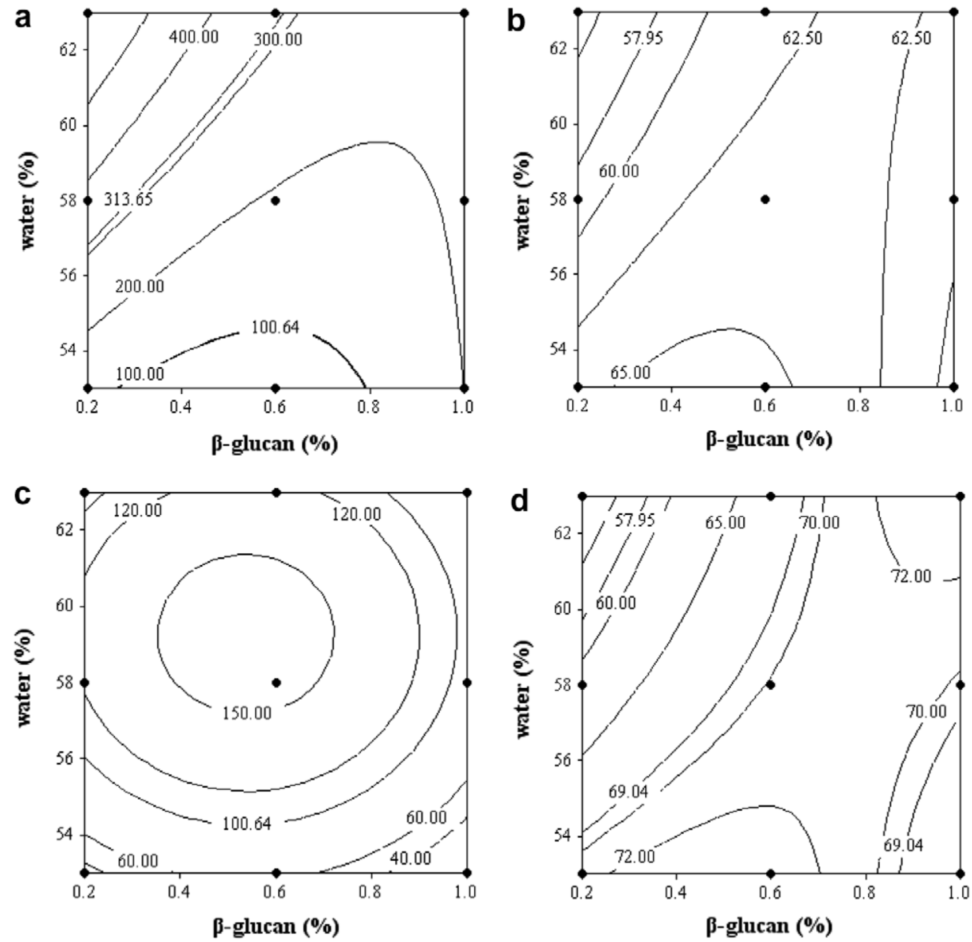

Fig. 4. Contour plots of maximum compliance, J_{max} (a and c), and elastic part of J_{max}, (J_e/J_{max}) (b and d) for Dion BG1, Dion BG2, respectively, measured under 50 Pa stress. The J_{max} and J_e/J_{max} values of the control doughs measured under low stress are 313.65 Pa^{-1}, 57.95% for Dion and 100.64 Pa^{-1}, 69.04% for Yekora dough, respectively.

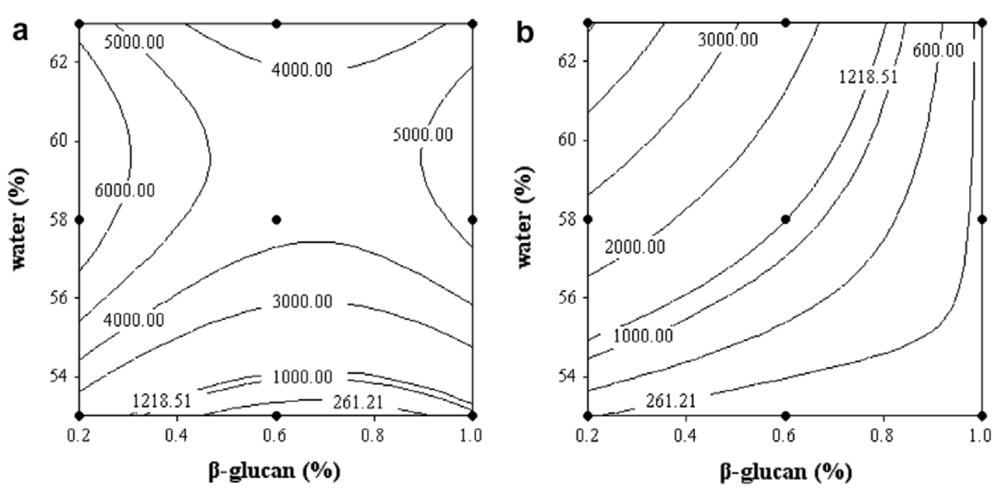

Fig. 5. Contour plots of maximum compliance, J_{max} (a and b) for Dion BG1, Dion BG2, respectively, measured under 300 Pa stress. J_{max} values of the control doughs measured under high stress are 1218.51 Pa^{-1} for Dion and 261.21 Pa^{-1} for Yekora dough, respectively.

Yekora control dough values for these parameters (100.64 Pa^{-1}, and 69.04%, of J_{max}-50 and J_e/J_{max}-50, respectively).

In the case of BG2 addition, the linear effect of the water on the J_{max}-50 and η_0-50 was significant but less pronounced than that of the polysaccharide (see the respective coefficients of J_{max}-50 and η_0-50 models in Table 5). Addition of BG2 decreased the J_{max}-50 value (<100.64 Pa^{-1}) and increased the η_0-50 (>134.33 Pa s) within the experimental window of this study (plots not shown). However, very low J_{max}-50 values could possibly lead to problems during the expansion phase of gas cells in the dough. Concerning J_e/J_{max}-50, the elasticity increases with addition of BG2 to Yekora control dough, exceeding the J_e/J_{max} values of the Yekora control.

From the respective model in Table 5 it was clear that the J_e/J_{max}-50 was positively correlated with the BG2 concentration and negatively correlated with the water level, i.e. an increase in BG2 concentration increased the J_e/J_{max}-50. Generally, the BG2 isolate required more water than BG1 in order to obtain the same value of the creep-parameters studied. Furthermore, the BG2 isolate produced more resistant to deformation and more elastic doughs than the BG1, a fact that could probably bring about problems during dough handling and the proofing process.

The regression coefficients of the maximum compliance, zero shear viscosity and the elastic part of the maximum compliance under high (300 Pa) creep stress (J_{max}-300, η_0-300 and J_e/J_{max}-300, respectively) are presented in Tables 4 and 5. In the experimental range used in this study, the responses J_{max}-300, η_0-300 and J_e/J_{max}-300 of the BG1-enriched Dion doughs, could not approach the respective parameter values of the Yekora control dough (261.21 Pa^{-1}, 45.12 Pa s, and 60.41%, respectively), except of a very small area in the case of J_{max}-300 (Table 4, Fig. 5a). Furthermore, less water than the optimum required for the β-glucan-free Dion control dough (56%) is needed for the BG1-enriched doughs to exhibit the same J_{max}-300, η_0-300 and J_e/J_{max}-300, as the Dion control dough (Table 4, Fig. 5a). The BG2 isolate decreased the J_{max}-300 values and increased the η_0-300 and J_e/J_{max}-300 values of the Dion doughs to a greater extent, compared to the BG1 isolate (Table 4, Fig. 5b). Only the J_{max}-300 and η_0-300 could reach similar values to those of the Yekora control dough (Table 4, Fig. 5b). In addition, although the elasticity of Dion doughs fortified with BG2 increased, the J_e/J_{max}-300 could not reach the respective value of the Yekora control dough within the experimental range of the tested variables (Table 4).

The effects of β-glucan addition on the J_{max}, η_0 and J_e/J_{max} of Yekora doughs measured at 300 Pa stress are shown in Table 5. Generally, the increase of the BG1 and BG2 concentration and the decrease of the water content in the Yekora doughs, lead to a decrease of the J_{max}-300 values and an increase of η_0-300 and J_e/J_{max}-300 values (plots not shown). Furthermore, the impact of BG2 was more pronounced than BG1 in lowering the J_{max}-300 values and increasing the η_0-300 and J_e/J_{max}-300 values of the Yekora doughs at the same level of polysaccharide addition.

Overall, a strong dependence of the molecular weight of the polysaccharide and the quality of the flour was observed in all responses measured under high and low creep stress level applied. At a low level of stress, the BG2 generated a greater effect on the creep-recovery responses than its lower molecular weight counterpart for both flours used. Differences between the creep-recovery parameters of the doughs measured under 50 Pa and 300 Pa stress were also observed. Doughs tested under low stress showed higher η_0 and J_e/J_{max}, but smaller J_{max} values than doughs measured under high applied stress. Skendi, Papageorgiou et al. (2009) have previously observed that β-glucan-enriched doughs with a consistency of 500 BU behave similarly. In general, the β-glucan-enriched doughs measured under 300 Pa could reach creep-recovery values of the Yekora and Dion control doughs with less water than the respective doughs with the same β-glucan content measured under 50 Pa stress.

4. Conclusions

The molecular weight of polysaccharides as well as the flour type affect the dynamic oscillatory and creep-recovery measurements of β-glucan-fortified doughs under low and high levels of applied stress. Both linear and quadratic effect of β-glucan and water content on the G', G'' and η^* were significant, whereas the interaction effects were significant only in the case of the poor quality flour (Dion). Generally, the β-glucan effect on G' values of the doughs depended on the quality of flour used. A pronounced plasticization effect of water in decreasing the G' values of β-glucan-free doughs was observed, with the G' values of Yekora doughs being always higher than those of the Dion doughs at the same water content. The β-glucan-enriched doughs made with Dion flour could reach G' values similar to those of control β-glucan-free Yekora dough (i.e. with a consistency of 500 BU), by changing the amount of water added, depending on the quantity and type of the β-glucan isolate used for fortification.

The effect of the lower molecular weight β-glucan isolate (BG1) was greater than that of water in the J_{max}-50 of Dion doughs, whereas for Yekora doughs, the high molecular β-glucan isolate (BG2) exhibited the greatest effect. The addition of BG2 resulted in lower J_{max}-50 values and higher η_0-50 and J_e/J_{max}-50 values of the doughs than those fortified with the BG1. Generally, the β-glucan-enriched Dion doughs could achieve similar viscoelasticity to that of the control β-glucan-free Yekora dough. The water quantity, at which such behavior can be achieved, depends on the quantity and type of the β-glucan used. Generally, when operating under low applied stress (50 Pa) the β-glucan-enriched doughs require more water than the level added to the control doughs in order to reach the creep-recovery responses of the respective control doughs. Under high applied stress (300 Pa), less water than that under low stress is required for the same β-glucan content in order to reach the creep-recovery responses of the respective control flour doughs. Based on the above results, the baking industry could process β-glucan-enriched wheat flour doughs with high water content, which varies with the polysaccharide concentration, that maintain good handling properties (similar to that of the good breadmaking quality control dough) and improved end-product nutritional quality.

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References

AACC (2000). 08-01 Ash—basic method (1983); 46-13 crude protein—micro-Kjeldahl method (1986). In *Approved methods of the AACC*. St. Paul, Minnesota: American Association of Cereal Chemists.

Amemiya, J. I., & Menjivar, J. A. (1992). Comparison of small and large deformation measurements to characterize the rheology of wheat-flour doughs. *Journal of Food Engineering, 16*(1–2), 91–108.

Behall, K. M., Scholfield, D. J., & Hallfrisch, J. (2004). Diets containing barley significantly reduce lipids in mildly hypercholesterolemic men and women. *American Journal of Clinical Nutrition, 80*(5), 1185–1193.

Cavallero, A., Empilli, S., Brighenti, F., & Stanca, A. M. (2002). High (1→3),(1→4)-β-glucan barley fractions in bread making and their effects on human glycemic response. *Journal of Cereal Science, 36*(1), 59–66.

Chaudhary, V. K., & Weber, F. E. (1990). Barley bran flour evaluated as dietary fiber ingredient in wheat bread. *Cereal Foods World, 35*(6), 560–562.

Collar, C., Andreu, P., Martinez, J. C., & Armero, E. (1999). Optimization of hydrocolloid addition to improve wheat bread dough functionality: A response surface methodology study. *Food Hydrocolloids, 13*(6), 467–475.

Collar, C., & Bollain, C. (2004). Impact of microbial transglutaminase on the viscoelastic profile of formulated bread doughs. *European Food Research and Technology, 218*(2), 139–146.

Dhingra, S., & Jood, S. (2004). Effect of flour blending on functional, baking and organoleptic characteristics of bread. *International Journal of Food Science and Technology, 39*(2), 213–222.

Edwards, N. M., Dexter, J. E., Scanlon, M. G., & Cenkowski, S. (1999). Relationship of creep-recovery and dynamic oscillatory measurements to durum wheat physical dough properties. *Cereal Chemistry, 76*(5), 638–645.

Edwards, N. M., Peressini, D., Dexter, J. E., & Mulvaney, S. J. (2001). Viscoelastic properties of durum wheat and common wheat dough of different strengths. *Rheologica Acta, 40*(2), 142–153.

Faubion, J. M., & Hoseney, R. C. (1990). The viscoelastic properties of wheat flour doughs. In H. Faridi & J. M. Faubion (Eds.), *Dough rheology and baked product texture* (pp. 29–66). New York: VanNostrand Reinhold.

Ferry, J. D. (1980). *Viscoelastic properties of polymers*. New York: Wiley.

Gallagher, E., O'Brien, C. M., Scannell, A. G. M., & Arendt, E. K. (2003). Use of response surface methodology to produce functional short dough biscuits. *Journal of Food Engineering, 56*(2–3), 269–271.

ICC-Standards (1994). No. 110/1: Determination of moisture content of cereals and cereal products (practical method) (1976); no. 155: Determination of wet gluten quantity and quality (Gluten Index ac. to Perten) of whole wheat meal and wheat flour (*Triticum aestivum*) (1994). In *Approved methods of the ICC*. Vienna: The ICC Standards.

Izydorczyk, M. S., Hussain, A., & MacGregor, A. W. (2001). Effect of barley and barley components on rheological properties of wheat dough. *Journal of Cereal Science, 34*(3), 251–260.

Junqueira, R. M., Castro, I. A., Areas, J. A. G., Silva, A. C. C., Scholz, M. B. S., Mendes, S., et al. (2007). Application of response surface methodology for the optimization of oxidants in wheat flour. *Food Chemistry, 101*(1), 131–139.

Kerckhoffs, D., Hornstra, G., & Mensink, R. P. (2003). Cholesterol-lowering effect of β-glucan from oat bran in mildly hypercholesterolemic subjects may decrease when beta-glucan is incorporated into bread and cookies. *American Journal of Clinical Nutrition, 78*(2), 221–227.

Khatkar, B. S., & Schofield, J. D. (2002). Dynamic rheology of wheat flour dough. II. Assessment of dough strength and bread-making quality. *Journal of the Science of Food and Agriculture, 82*(8), 823–826.

Knuckles, B. E., Hudson, C. A., Chiu, M. M., & Sayre, R. N. (1997). Effect of β-glucan barley fractions in high-fiber bread and pasta. *Cereal Foods World, 42*(2), 94–99.

Lazaridou, A., Biliaderis, C. G., & Izydorczyk, M. S. (2003). Molecular size effects on rheological properties of oat β-glucans in solution and gels. *Food Hydrocolloids, 17*(5), 693–712.

Lefebvre, J. (2006). An outline of the non-linear viscoelastic behaviour of wheat flour dough in shear. *Rheologica Acta, 45*(4), 525–538.

Létang, C., Piau, M., & Verdier, C. (1999). Characterization of wheat flour–water doughs. Part I: Rheometry and microstructure. *Journal of Food Engineering, 41*(2), 121–132.

McCleary, B. V., & Glennie-Holmes, M. (1985). Enzymic quantification of (1→3),(1→4)-β-D-glucan in barley and malt. *Journal of the Institute of Brewing, 91*(5), 285–295.

Navickis, L. L., Anderson, R. A., Bagley, E. B., & Jasberg, B. K. (1982). Viscoelastic properties of wheat-flour doughs – Variation of dynamic moduli with water and protein content. *Journal of Texture Studies, 13*(2), 249–264.

Paredes-Lopez, O., & Bushuk, W. (1983). Development and undevelopment of wheat dough by mixing – Physicochemical studies. *Cereal Chemistry, 60*(1), 19–23.

Petrofsky, K. E., & Hoseney, R. C. (1995). Rheological properties of dough made with starch and gluten from several cereal sources. *Cereal Chemistry, 72*(1), 53–58.

Phan-Thien, N., & Safari-Ardi, M. (1998). Linear viscoelastic properties of flour–water doughs at different water concentrations. *Journal of Non-Newtonian Fluid Mechanics, 74*(1–3), 137–150.

Rosell, C. M., Santos, E., & Collar, C. (2006). Mixing properties of fibre-enriched wheat bread doughs: A response surface methodology study. *European Food Research and Technology, 223*(3), 333–340.

Safari-Ardi, M., & Phan-Thien, N. (1998). Stress relaxation and oscillatory tests to distinguish between doughs prepared from wheat flours of different varietal origin. *Cereal Chemistry, 75*(1), 80–84.

Skendi, A., Biliaderis, C. G., Lazaridou, A., & Izydorczyk, M. S. (2003). Structure and rheological properties of water soluble β-glucans from oat cultivars of *Avena sativa* and *Avena bysantina*. *Journal of Cereal Science, 38*(1), 15–31.

Skendi, A., Biliaderis, C. G., Papageorgiou, M., & Izydorczyk, M. S. (2009). Effect of two barley β-glucan isolates on wheat flour dough and bread properties. *Food Chemistry*, in press.

Skendi, A., Papageorgiou, M., & Biliaderis, C. G. (2009). Effect of barley β-glucan molecular size and level on wheat dough rheological properties. *Journal of Food Engineering, 91*(4), 594–601.

Vaikousi, H., Biliaderis, C. G., & Izydorczyk, M. S. (2004). Solution flow behavior and gelling properties of water-soluble barley (1→3),(1→4)-β-glucans varying in molecular size. *Journal of Cereal Science, 39*(1), 119–137.

Wang, L., Newman, R. K., Newman, C. W., & Hofer, P. J. (1992). Barley β-glucans alter intestinal viscosity and reduce plasma-cholesterol concentrations in chicks. *Journal of Nutrition, 122*(11), 2292–2297.

Wood, P. J., Weisz, J., & Blackwell, B. A. (1991). Molecular characterization of cereal β-D-glucans – Structural-analysis of oat β-D-glucan and rapid structural evaluation of β-D-glucans from different sources by high-performance liquid-chromatography of oligosaccharides released by lichenase. *Cereal Chemistry, 68*(1), 31–39.

Wood, P. J., Weisz, J., & Blackwell, B. A. (1994). Structural studies of (1→3),(1→4)-β-D-glucans by C(13)-nuclear magnetic-resonance spectroscopy and by rapid analysis of cellulose-like regions using high-performance anion-exchange chromatography of oligosaccharides released by lichenase. *Cereal Chemistry, 71*(3), 301–307.