

THE EFFECT OF pH AND STABILIZATION TIME ON THE APPARENT VISCOSITY OF AQUEOUS DISPERSIONS OF WHOLEMEAL BARLEY FLOUR

Piotr Zarzycki^{id}, Anna Wirkijowska^{id}, Aldona Sobota^{id}, Emilia Sykut-Domańska^{id}

Division of Engineering and Cereals Technology, Department of Plant Food Technology and Gastronomy
University of Life Science in Lublin, Skromna, 20-704, Lublin, Poland
e-mail: anna.wirkijowska@up.lublin.pl

Abstract. The effect of stabilization time (0.5-3 h), pH (1.5-12), and shear rate (200-1200 s⁻¹) on the apparent viscosity of the aqueous dispersion of wholemeal barley flour was determined. Six barley flours with different (1→3), (1→4)β-D-glucan contents were used in this study. The results revealed the significant effect of pH on apparent viscosity, but no unidirectional relationships were observed. The highest values of apparent viscosity were obtained at the highest pH (pH 12). An increase in the apparent viscosity of the barley flour dispersion with the passage of time was observed. A significant linear correlation between the apparent viscosity of aqueous dispersions of wholemeal barley flour and the content of (1→3), (1→4)β-D glucans in wholemeal barley flour was found. These results suggest that measurements of apparent viscosity may be used to rapidly estimate (1→3), (1→4)β-D glucan content in barley wholemeal flour. The content of (1→3), (1→4)β-D glucans may be determined with an accuracy of 87% by the apparent viscosity of the barley flour dispersion ($R^2 = 0.87$) with the following measurement conditions: 10% w/w wholemeal barley flour water dispersions, shear rate 1200 s⁻¹, pH 12, 1.5-2 h time stabilization.

Keywords: apparent viscosity; barley; dietary fibre; pH; (1→3), (1→4)β-D glucans

INTRODUCTION

The incidence of diseases, which are mainly associated with changes in dietary habits and lifestyle, has been increasing to a greater extent in recent times; therefore, it has become very important to promote the consumption of food with high levels of dietary fibre. Due to its nutritional properties, especially the high content of soluble dietary fibre (SDF), barley and oats are considered to be the most beneficial grains in the human diet (Alminger and Eklund-Jonsson 2008, Friedrich 2003). The main mechanism responsible for the physiological effects of SDF is its



ability to increase the viscosity of the gastric contents (Dikeman and Fahey 2006, Wood 2007). Viscous dietary fibre includes many soluble polysaccharides such as gums, pectins, and β -glucans. The main component of SDF in both barley and oats is (1 \rightarrow 3), (1 \rightarrow 4)- β -D-glucan (Hallfrisch and Behall 2000, Dikeman and Fahey 2006). The β -glucan found in oats usually exhibits a higher viscosity due to its long molecular chains (Beer and Wood 1997), but according to Burkus and Temelli (2005), it may be expected that both oat and barley β -glucans would behave alike at similar molecular weights. Scientific evidence links the intake of β -glucans to a lowering of the post-meal concentration of blood glucose (Brenelli *et al.* 1997), and also to a decrease in blood cholesterol levels (Danielson *et al.* 1997). However, according to Danielson *et al.* (1997) there is no linear relationship between the viscosity of wholemeal dispersions and their physiological effects.

One of the problems encountered during technological processes is the rapid determination of the fibre content in both the raw material and product. The major drawbacks of enzymatic and chemical methods which exclude these methods from rapid control procedures are their time-consuming nature and cost. Measurement of the apparent viscosity of extracts and dispersions could be a rapid method allowing for the determination of dietary fibre content in cereal products, such as flour (Svihus *et al.* 2000, Mager *et al.* 2003, Zarzycki and Sobota 2015). Therefore, it is important to establish the effects of the measurement parameters (i.e. shear stress, pH, temperature) on viscosity (Zhang 1997, Burkus and Temelli 2005, Dikeman and Fahey 2006).

The study aimed at defining the parameters of viscosity measurement in order to estimate the content of β -glucans in wholemeal barley flour. The effect of pH, time stabilization, and shear rate on the apparent viscosity of wholemeal flour dispersions was determined. The correlation between the apparent viscosity of barley flour dispersions and the content of the dietary fibre fraction: total, insoluble, soluble, and (1 \rightarrow 3), (1 \rightarrow 4)- β -D-glucans in wholemeal barley flour was determined.

MATERIALS AND METHODS

Raw materials and chemical analysis

The experimental material consisted of wholemeal barley flours, obtained through the laboratory milling (universal impact grinder H-111/3, gap of 0.2 mm, Agromet, Jawor, Poland) of six barley cultivar grains (Strzelce, Poland: 1-STH 4480, 2-STH 4510, 3-STH 4476, 4-STH 5026, 5-STH5206, 6-STH 5029), with different contents of (1 \rightarrow 3), (1 \rightarrow 4)- β -D glucans.

The content of total dietary fibre (TDF), soluble dietary fibre (SDF), insoluble dietary fibre (IDF) (AOAC Method 991.43; Method 32-07.01), and (1 \rightarrow 3), (1 \rightarrow 4)- β -D glucans (AACC, Method 32-23; AOAC, Method 995.16.) was determined

based on the procedures and enzymes from Megazyme (Megazyme International Ireland, Bray, Ireland). All measurements were made in three replications. Table 1 presents the chemical composition of the wholemeal barley flours.

Table 1. Chemical composition of wholemeal barley flour (% d.b.)

Barley flour	Ash	Protein	Fat	(1-3) (1-4) β -D glucan	TDF	SDF	IDF
1	1.99 ^{ab} ±0.01	10.79 ^{bc} ±0.22	1.91 ^{bc} ±0.02	6.02 ^a ± 0.05	17.97 ^a ±0.07	6.90 ^a ± 0.23	11.07 ^b ± 0.3
2	2.02 ^{ab} ±0.01	12.27 ^{ab} ±0.26	1.88 ^c ±0.01	5.22 ^b ± 0.08	16.82 ^{ab} ±0.49	7.11 ^a ± 0.39	9.71 ^{cd} ± 0.1
3	1.88 ^c ±0.01	11.15 ^{abc} ±1.16	1.99 ^a ±0.03	4.88 ^c ± 0.06	15.96 ^b ±0.44	6.59 ^a ± 0.39	9.38 ^d ± 0.05
4	2.03 ^{ab} ±0.08	9.74 ^c ±0.88	1.81 ^d ±0.02	4.37 ^d ± 0.13	16.72 ^{ab} ±0.3	6.65 ^a ± 0.21	10.06 ^c ± 0.09
5	2.05 ^a ±0.01	12.44 ^a ±0.03	1.94 ^{ab} ±0.01	3.80 ^f ± 0.10	15.74 ^b ±1.06	3.90 ^c ± 0.76	11.84 ^a ± 0.31
6	1.95 ^{bc} ±0.00	9.96 ^c ±0.40	1.82 ^d ±0.03	4.14 ^e ± 0.11	16.07 ^{ab} ±0.76	5.32 ^b ± 0.44	10.75 ^b ± 0.32

Explanatory notes: table shows mean values (n = 3) ± standard deviation; means in the column denoted by different small letters differ statistically significantly (Duncan; $p \leq 0.05$); TDF – Total dietary fibre; SDF – Soluble dietary fibre; IDF – Insoluble dietary fibre; Barley cultivars: 1 – STH 4480, 2 – STH 4510, 3 – STH 4476, 4 – STH 5026, 5 – STH5206, 6 – STH 5029.

Rheological measurements

The apparent viscosity of the barley flour dispersions was measured using a rotary rheometer (Mettler Rheomat RM 180, Mettler-Toledo AG, Switzerland, software RSI Orchestrator ver. V6.5.8.), with coaxial cylinders without the bottom cylinder guard (cylinder diameters: measuring tube 32.54 mm, measuring bob 30 mm, and height 45 mm; shear rate 200-1200 s^{-1} at increments of 200 s^{-1}). The measurement was based on the method described by Zarzycki and Sobota (2015). Wholemeal barley flour dispersions (10% w/w; the moisture content of each flour was considered for the purpose of calculating the appropriate amount of water to add) were prepared with distilled water (50°C, pH of 1.5, 4.5, 7.0, 9.5, and 12.0). The pH of the distilled water was adjusted beforehand by the addition of 5% NaOH or 5% HCl. The dispersions (300 mL), after 5 min of mixing (Magnetic stirrer type MM6, Poznań, Poland, temp. 50°C), were placed in a heated laboratory shaker (type 357, “Elpin Plus” s.c., Lubawa, Poland; frequency 200 $rev \cdot min^{-1}$, amplitude 3, temperature 50°C). The samples were covered to prevent evaporation. During viscosity measurements, agitation was stopped and the cylinders (maintained at the temperature of measurement), were immersed in the suspension. The apparent viscosity of the flour dispersions were measured after 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0 h. The stabilization time was defined as the period from the placement of samples in a heated laboratory shaker to viscosity measurement. All measurements were performed in triplicate.

Statistical analysis

Mean values, standard deviations, significance of differences between mean values (Duncan test, $p \leq 0.05$), and linear correlation (Pearson, $p \leq 0.05$ and $p \leq 0.1$) between the apparent viscosity of the wholemeal barley flour dispersions and the content of dietary fibre fractions were determined (SAS version 9.2.), and also the equations of linear regression were plotted.

RESULTS AND DISCUSSION

The study showed the significant effects of barley cultivar, pH, shear rate, and stabilization time on the apparent viscosity of aqueous dispersions of wholemeal barley flours (Tab. 2). Depending on their viscosity as a function of shear rate, stress, deformation history, fluids can be characterized as either Newtonian or non-Newtonian. This study showed the different effects of shear rate on the apparent viscosity of barley flour suspensions depending on the stabilization time (data not shown). A thickening behaviour, independent of pH, for all tested suspensions after 0.5 h of stabilization time was observed. During the remainder of the stabilization time (1-3 h) the dispersions displayed pseudoplastic flow behaviour. An example of the thickening and pseudoplastic behaviour of a barley flour suspension (sample no 1) tested after 0.5 and 3 h of stabilization time is shown in Figure 1. The higher the pH, the faster the changes in the rheological properties of suspensions, which occur. Further research is warranted in order to identify the causes of this phenomenon.

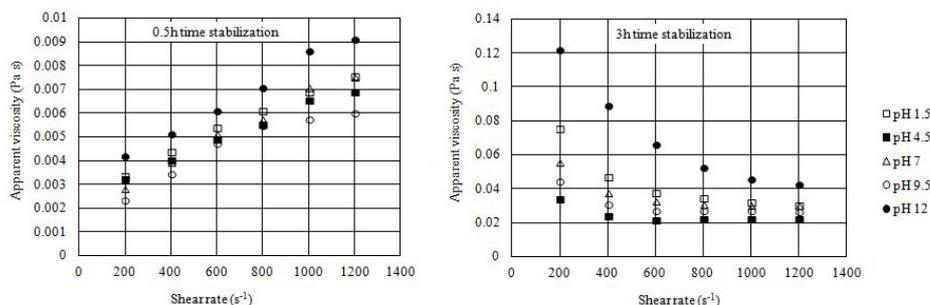


Fig. 1. Examples (sample no. 1) of thickening and pseudoplastic behaviour of barley flour suspensions at different pH levels tested after 0.5 and 3 h time of stabilization.

To determine the potential use of viscosity measurements in estimating the quantity of (1→3), (1→4)-β-D glucans a broad range of pH values was used. However, neither extremely high nor extremely low pH values are recommended for food production. The highest values of viscosity were observed at the highest pH level (pH 12). The increase in viscosity associated with increasing the pH values of the suspensions may be due to the different structural characteristics of β-glucan soluble at different pH values. Izydorczyk *et al.* (1998)

Table 2. Apparent viscosity (mPa·s) of aqueous dispersions (10% w/w) of wholemeal barley flour (shear rate 1200 s⁻¹, pH 1.5-12)

Barley flour	pH				
	1.5	4.5	7	9.5	12
Stabilization time 0.5 h					
1	7.6 ^{Bb} ± 0.1	6.9 ^{Bc} ± 0.1	7.5 ^{Bb} ± 0.1	6.0 ^{CBd} ± 0.1	9.1 ^{Ea} ± 0.1
2	7.9 ^{Ac} ± 0.0	7.7 ^{Ad} ± 0.1	8.0 ^{Ab} ± 0.1	6.1 ^{CBe} ± 0.1	12.4 ^{Aa} ± 0.1
3	7.8 ^{Ab} ± 0.1	6.9 ^{Bc} ± 0.1	6.6 ^{Dd} ± 0.1	6.1 ^{Bc} ± 0.1	11.5 ^{Ba} ± 0.1
4	7.4 ^{Cb} ± 0.1	6.9 ^{Bc} ± 0.0	6.8 ^{Cc} ± 0.1	5.9 ^{Cd} ± 0.3	9.2 ^{Ea} ± 0.1
5	6.5 ^{Ec} ± 0.2	6.4 ^{Cc} ± 0.1	7.0 ^{Cb} ± 0.2	6.5 ^{Ac} ± 0.1	10.9 ^{Ca} ± 0.1
6	6.9 ^{Db} ± 0.1	6.1 ^{Dcd} ± 0.2	6.3 ^{Ec} ± 0.4	6.0 ^{Cd} ± 0.1	10.0 ^{Da} ± 0.1
Stabilization time 1 h					
1	9.3 ^{Bb} ± 0.1	8.9 ^{Dd} ± 0.1	8.5 ^{Bc} ± 0.0	9.0 ^{Cc} ± 0.1	17.8 ^{Aa} ± 0.1
2	10.2 ^{Ac} ± 0.1	10.7 ^{Ab} ± 0.2	9.5 ^{Ad} ± 0.1	9.0 ^{Cc} ± 0.1	17.4 ^{Ba} ± 0.1
3	10.2 ^{Ab} ± 0.1	10.1 ^{Bb} ± 0.1	8.6 ^{Bd} ± 0.2	9.6 ^{Bc} ± 0.1	16.8 ^{Ca} ± 0.1
4	9.0 ^{Cc} ± 0.1	9.5 ^{Cb} ± 0.1	8.6 ^{Bd} ± 0.1	9.6 ^{Bb} ± 0.1	16.3 ^{Da} ± 0.1
5	7.6 ^{Ed} ± 0.1	8.7 ^{Ec} ± 0.1	8.6 ^{Bc} ± 0.4	9.8 ^{Ab} ± 0.1	14.3 ^{Ea} ± 0.1
6	8.5 ^{Dcb} ± 0.1	8.4 ^{Fc} ± 0.1	7.7 ^{Cd} ± 0.1	8.5 ^{Db} ± 0.1	13.8 ^{Fa} ± 0.1
Stabilization time 1.5 h					
1	12.0 ^{Bd} ± 0.2	13.8 ^{Cc} ± 0.1	10.2 ^{De} ± 0.1	16.2 ^{Bb} ± 0.1	27.8 ^{Aa} ± 0.2
2	12.0 ^{Be} ± 0.2	16.0 ^{Ac} ± 0.1	12.3 ^{Ad} ± 0.1	19.8 ^{Ab} ± 0.1	23.8 ^{Ba} ± 0.1
3	14.5 ^{Ad} ± 0.1	15.0 ^{Bc} ± 0.1	11.3 ^{Be} ± 0.2	15.6 ^{Cb} ± 0.1	21.1 ^{Da} ± 0.0
4	11.2 ^{Cc} ± 0.1	11.2 ^{De} ± 0.1	10.7 ^{Cd} ± 0.1	12.9 ^{Db} ± 0.1	22.5 ^{Ca} ± 0.0
5	8.5 ^{Ee} ± 0.1	10.1 ^{Fc} ± 0.1	9.6 ^{Ed} ± 0.2	12.6 ^{Eb} ± 0.1	17.7 ^{Ea} ± 0.1
6	10.9 ^{Dc} ± 0.1	10.8 ^{Ec} ± 0.1	10.2 ^{Dd} ± 0.1	11.7 ^{Fb} ± 0.0	17.4 ^{Fa} ± 0.1
Stabilization time 2 h					
1	13.7 ^{Ed} ± 0.1	15.5 ^{Cc} ± 0.1	11.7 ^{Ce} ± 0.1	18.3 ^{Bb} ± 0.1	36.3 ^{Aa} ± 0.1
2	16.2 ^{Be} ± 0.1	17.8 ^{Ac} ± 0.1	17.3 ^{Ad} ± 0.1	20.4 ^{Ab} ± 0.0	29.9 ^{Ba} ± 0.1
3	16.5 ^{Ab} ± 0.1	15.4 ^{Cd} ± 0.1	12.9 ^{Be} ± 0.1	15.7 ^{Dc} ± 0.1	28.1 ^{Da} ± 0.1
4	15.2 ^{Dc} ± 0.1	13.8 ^{Dd} ± 0.1	11.3 ^{De} ± 0.1	15.9 ^{Cb} ± 0.1	29.2 ^{Ca} ± 0.1
5	9.8 ^{Fe} ± 0.1	12.0 ^{Ec} ± 0.1	11.6 ^{Cd} ± 0.1	14.5 ^{Eb} ± 0.0	20.7 ^{Fa} ± 0.1
6	15.3 ^{Cc} ± 0.1	15.8 ^{Bb} ± 0.1	11.2 ^{De} ± 0.2	13.0 ^{Fd} ± 0.1	21.7 ^{Ea} ± 0.1
Stabilization time 2.5 h					
1	16.4 ^{Dc} ± 0.1	16.0 ^{Dd} ± 0.1	15.9 ^{Bd} ± 0.1	22.3 ^{Ab} ± 0.2	34.6 ^{Ca} ± 0.0
2	16.8 ^{Ce} ± 0.1	18.0 ^{Bc} ± 0.1	17.9 ^{Ad} ± 0.1	21.8 ^{Bb} ± 0.1	35.6 ^{Aa} ± 0.1
3	16.9 ^{Cb} ± 0.1	16.2 ^{Cc} ± 0.1	13.0 ^{De} ± 0.1	15.7 ^{Dd} ± 0.1	32.0 ^{Da} ± 0.1
4	17.5 ^{Ad} ± 0.1	18.8 ^{Ac} ± 0.1	14.8 ^{Ce} ± 0.1	21.0 ^{Cb} ± 0.0	35.2 ^{Ba} ± 0.1
5	12.6 ^{Ed} ± 0.1	14.3 ^{Eb} ± 0.1	12.2 ^{Fe} ± 0.1	13.9 ^{Ec} ± 0.2	24.4 ^{Fa} ± 0.0
6	17.4 ^{Bb} ± 0.1	13.9 ^{Fc} ± 0.0	12.6 ^{Fe} ± 0.2	12.8 ^{Fd} ± 0.1	26.1 ^{Ea} ± 0.1
Stabilization time 3 h					
1	31.0 ^{Ab} ± 0.2	23.3 ^{Be} ± 0.1	30.3 ^{Ac} ± 0.1	27.1 ^{Bd} ± 0.1	42.6 ^{Aa} ± 0.0
2	19.4 ^{Fe} ± 0.1	21.6 ^{Cd} ± 0.1	21.9 ^{Dc} ± 0.2	30.9 ^{Ab} ± 0.1	37.4 ^{Ba} ± 0.1
3	22.3 ^{Bc} ± 0.1	21.5 ^{Cd} ± 0.1	22.9 ^{Cb} ± 0.1	21.3 ^{Ee} ± 0.1	35.3 ^{Da} ± 0.1
4	20.0 ^{Ee} ± 0.1	21.0 ^{Dc} ± 0.1	20.2 ^{Fd} ± 0.1	24.4 ^{Cb} ± 0.2	37.0 ^{Ca} ± 0.0
5	20.2 ^{Dd} ± 0.4	18.2 ^{Ee} ± 0.1	21.2 ^{Ec} ± 0.2	22.8 ^{Db} ± 0.1	26.3 ^{Fa} ± 0.1
6	21.3 ^{Cd} ± 0.1	25.5 ^{Ab} ± 0.6	25.4 ^{Bb} ± 0.2	24.4 ^{Cc} ± 0.1	27.9 ^{Fa} ± 0.1

Explanatory notes: table shows mean values (n = 3) ± standard deviation, means in the column denoted by different capital letters (A-G) and in the row by small letter (a-e) differ statistically significantly (Duncan; p ≤ 0.05); Barley cultivars: 1 – STH 4480, 2 – STH 4510, 3 – STH 4476, 4 – STH 5026, 5 – STH5206, 6 – STH 5029.

showed that the alkali-soluble β -glucan of barley has a higher ratio of β -(1/4): β -(1/3)-linkages, a higher ratio of cellotriosyl:cellotetraosyl units, and larger amounts of contiguous β -(1/4)-linked segments than water-extractable β -glucan.

For most assays, the suspension viscosity at pH 1.5 was higher compared to the viscosity measured at pH 7. Similar results were reported for barley grain extracts (Mager *et al.* 2003). Hirashima and co-workers (2005) suggested that, the increase in viscosity at a low pH level, is caused by the glucose chains leached out from the starch granules. On the contrary, Dawkins and Nnanna (1995) reported that the viscosity of oat gums does not depend on the pH level (from pH 2 up to 10). Our study showed that the viscosity of barley flour dispersions depends significantly on pH; however, the changes in viscosity were not linear.

The viscosity of flour dispersions changes during the passage of time, and a significant increase in viscosity was observed (Duncan; $p \leq 0.05$). Similar results were noted in earlier studies for oats (Zhang *et al.* 1997, Zarzycki and Sobota 2015). This indicates the need to strictly define the stabilization time.

The increase in viscosity with time presumably occurs due to the increasing extraction of the β -glucan polymer, the polymers hydration, swelling of starch granules, and the low activity of amylolytic enzymes in flour. Goody *et al.* (2005) reported that at a low amylolytic activity an increase in viscosity may be observed. However, it must be stressed that the high level of amylolytic activity leads to a decrease in viscosity, especially over extended time periods, due to liquefaction processes. A study by Mager *et al.* (2003) showed a decrease in barley grain extract viscosity after a 6-hour period. During heating at a constant temperature, the starch granules swell, some of them rupture and release their contents, which contributes to an increase in viscosity. The increase in viscosity indicates that more water is taken up by starch, protein and/or gums in the sample resulting in more viscous slurries (Gray *et al.* 2010). According to Zhang and co-workers (Zhang *et al.* 1997), a higher slurry incubation temperature and smaller particle size may stimulate the rate and extent of polymer hydration.

Table 3 presents the correlations (Pearson) between the apparent viscosity of the aqueous wholemeal barley flour dispersions and the content of TDF, IDF, SDF, and (1 \rightarrow 3),(1 \rightarrow 4)- β -D glucans under different measurement conditions. The correlation is highly dependent on pH and the stabilization time. The highest significant correlations (Pearson, $p \leq 0.05$) were found between the dietary fibre fraction and the viscosity of the barley flour dispersions measured at pH 12 and 1-3 h stabilization time. The correlation coefficients, depending on the testing time, are within the range of 0.79-0.95, 0.74-0.94, and 0.74-0.93 respectively for the SDF, TDF, and (1 \rightarrow 3),(1 \rightarrow 4)- β -D glucans. A negative correlation was recorded for the IDF. There were no significant correlations ($p < 0.05$) between the content of TDF, SDF, IDF, and (1 \rightarrow 3), (1 \rightarrow 4)- β -D glucans and the dispersion viscosity measured at pH values ranging from 4.5 to 9.5. In contrast to these finding, Zarzycki and Sobota (2015) found high correlations between TDF, (1 \rightarrow 3),(1 \rightarrow 4)- β -D glucans, and viscosity at pH 1.5 for oat flour dispersion.

Table 3. Correlation between the apparent viscosity of aqueous dispersions (10% w/w) of wholemeal barley flour (n = 6) and dietary fibre fractions

Dietary fibre fraction	pH				
	1.5	4.5	7	9.5	12
Stabilization time 0.5 h					
(1-3) (1-4) β-D glucan	0.77**	0.62	0.63	-0.41	-0.06
TDF	0.52	0.45	0.62	-0.50	-0.43
SDF	0.96*	0.75**	0.44	-0.76**	0.01
IDF	-0.82*	-0.60	-0.05	0.58	-0.39
Stabilization time 1 h					
(1-3) (1-4) β-D glucan	0.67	0.36	0.33	-0.28	0.88*
TDF	0.34	0.08	0.20	-0.29	0.74**
SDF	0.89*	0.67	0.40	-0.21	0.87*
IDF	-0.88*	-0.83*	-0.36	0.03	-0.51
Stabilization time 1.5 h					
(1-3) (1-4) β-D glucan	0.57	0.75**	0.39	0.73**	0.93*
TDF	0.21	0.38	0.12	0.47	0.94*
SDF	0.76**	0.78**	0.72**	0.69	0.79**
IDF	-0.84*	-0.70**	-0.86*	-0.50	-0.23
Stabilization time 2 h					
(1-3) (1-4) β-D glucan	0.38	0.61	0.35	0.77**	0.93*
TDF	0.17	0.38	0.11	0.67	0.91*
SDF	0.79**	0.72**	0.46	0.72**	0.85*
IDF	-0.91*	-0.63	-0.52	-0.37	-0.33
Stabilization time 2.5 h					
(1-3) (1-4) β-D glucan	0.39	0.36	0.72**	0.75**	0.74**
TDF	0.35	0.42	0.73**	0.85*	0.71**
SDF	0.78**	0.75**	0.77**	0.79**	0.95*
IDF	-0.73**	-0.65	-0.38	-0.31	-0.65
Stabilization time 3 h					
(1-3) (1-4) β-D glucan	0.75**	0.34	0.67	0.55	0.90*
TDF	0.75**	0.33	0.65	0.62	0.87*
SDF	0.30	0.37	0.23	0.51	0.90*
IDF	0.26	-0.20	0.28	-0.13	-0.43

Explanatory notes: TDF – Total dietary fibre; SDF – Soluble dietary fibre; IDF – Insoluble dietary fibre; pH of aqueous dispersions (10% w/w) of wholemeal barley flour; correlation coefficient statistically significant at * $p \leq 0.05$ and ** $p \leq 0.1$.

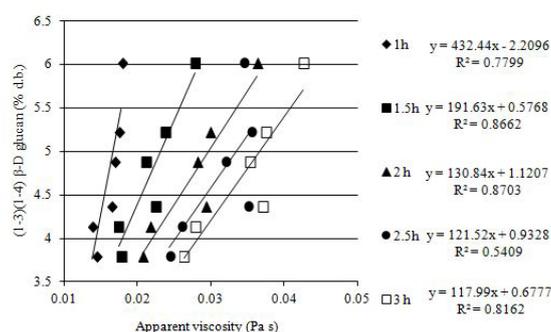


Fig. 2. Influence of the content of (1→3), (1→4)–β–D glucans on the apparent viscosity of aqueous dispersions (10% w/w) of wholemeal barley flour (pH 12, shear rate 1200 s^{-1} , 1-3 h stabilization time).

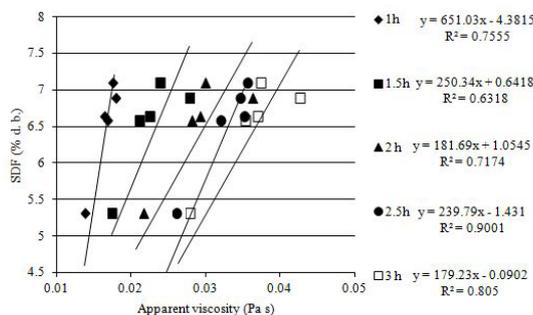


Fig. 3. Influence of the content of soluble dietary fibre (SDF) on the apparent viscosity of aqueous dispersions (10% w/w) of wholemeal barley flour (pH 12, shear rate 1200 s^{-1} , 1-3 h stabilization time).

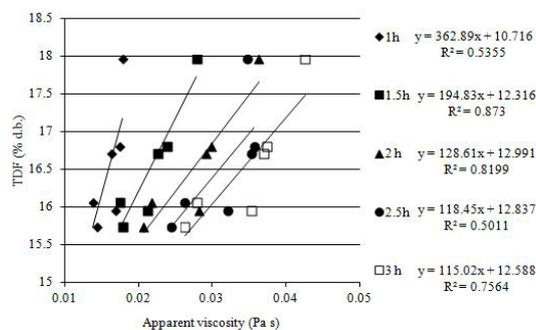


Fig. 4. Influence of the content of total dietary fibre (TDF) on the apparent viscosity of aqueous dispersions (10% w/w) of wholemeal barley flour (pH 12, shear rate 1200 s^{-1} , 1-3 h stabilization time).

Figures 2-4 present a correlation between the dispersion viscosity and dietary fibre fraction content and also the regression equations for measurement conditions, which give the highest coefficients of correlation (pH 12, shear rate 1200 s^{-1}). As shown in Figure 2 the content of SDF may be partially explained (63-90%) by the viscosity of the dispersion, depending on the stabilization time. Slightly lower correlations were obtained for (1→3), (1→4)- β -D glucans (Fig. 3, $R^2 = 0.54-0.87$), and for TDF (Fig. 4, $R^2 = 0.53-0.87$).

CONCLUSIONS

The results presented support the possibility of using viscosity measurements for the rapid estimation of the content of dietary fibre fractions, especially SDF and (1→3),(1→4)- β -D glucans, in barley wholemeal flour. With the application of suitable measurement conditions (10% w/w wholemeal barley flour water dispersions, shear rate 1200 s^{-1} , pH 12, 1.5-2 h time stabilization), the content of (1→3),(1→4)- β -D glucans may be determined with an accuracy of 87% by the apparent viscosity of the barley flour dispersion ($R^2 = 0.87$).

Conflict of interest: The Authors does not declare conflict of interest.

REFERENCES

- AACC, 2000. American Association of Cereal Chemistry International, St. Paul, Minnesota, USA.
- Alminger M., Eklund-Jonsson Ch., 2008. Whole-grain cereal products based on a high-fibre barley or oat genotype lower post-prandial glucose and insulin responses in healthy humans. *Eur. J. Nutr.*, 47, 294-300, <https://doi.org/10.1007/s00394-008-0724-9>
- AOAC, 1990. Official Methods of Analysis. 15th ed. Association of Official Analytical Chemists. Arlington, VA.
- Beer M.U., Wood P.J., Weisz J., 1997. Molecular weight distribution and (1→3)(1→4)-β-D-glucan content of consecutive extracts of various oat and barley cultivars. *Cereal Chem.*, 74, 476-480, <https://doi.org/10.1094/CCHEM.1997.74.4.476>
- Brenelli S.L., Campos S.D.S., Saad M.J.A., 1997. Viscosity of gums in vitro and their ability to reduce postprandial hyperglycemia in normal subjects. *Brazilian J. Med. Biol. Res.*, 30, 1437-1440, <https://doi.org/10.1590/S0100-879X1997001200009>
- Burkus Z., Temelli F., 2005. Rheological properties of barley β-glucan. *Carbohydr. Polym.*, 59, 459-465, <https://doi.org/10.1016/j.carbpol.2004.10.012>
- Danielson A.D., Newman R.K., Newman C.W., Berardinelli J.G., 1997. Lipid levels and digesta viscosity of rats fed a high-fibre barley milling fraction. *Nutr. Res.*, 17, 515-522, [https://doi.org/10.1016/S0271-5317\(97\)00016-X](https://doi.org/10.1016/S0271-5317(97)00016-X)
- Dawkins N.L., Nnanna I.A., 1995. Studies on oat gum [(1-3, 1-4)-β-D-glucan]: composition, molecular weight estimation and rheological properties. *Food Hydrocoll.*, 9, 1-7, [https://doi.org/10.1016/S0268-005X\(09\)80188-4](https://doi.org/10.1016/S0268-005X(09)80188-4)
- Dikeman Ch.L., Fahey G.C.Jr., 2006. Viscosity as related to dietary fibre. A review. *Crit. Rev. Food Sci. Nutr.*, 46, 649-663, <https://doi.org/10.1080/10408390500511862>
- Friedrich M., 2003. The effects of diet enrichment with hull-less oat cultivar on glucose, lipid, lipoprotein, fibrinogen and estradiol contents in the blood of post-mastectomy women. *Pol. J. Food Nutr. Sci.*, 12(53), 69-74.
- Goode D.L., Ulmer H.M., Arendt E.K., 2005. Model studies to understand the effects of amylase additions and pH adjustment on the rheological behaviour of simulated brewery mashes. *J. Inst. Brew.*, 111(2), 153-164, <https://doi.org/10.1002/j.2050-0416.2005.tb00661.x>
- Gray D., El-Sayed M., Abdel-Aal, Seetharaman K., Kakuda Y., 2010. Differences in viscosity and textural properties of selected barley cultivars as influenced by pearling and cooking. *Food Chem.*, 120, 402-409, <https://doi.org/10.1016/j.foodchem.2009.10.020>
- Hallfrisch J., Behall K., 2000. Mechanisms of the effects of grains on insulin and glucose responses. *J. Am. Coll. Nutr.*, 19, 320-325, <https://doi.org/10.1080/07315724.2000.10718967>
- Hirashima M., Takahashi R., Nishinari K., 2005. Effect of adding acids before and after gelatinization on the viscoelasticity of cornstarch pastes. *Food Hydrocolloid.*, 19(5), 909-914, <https://doi.org/10.1016/j.foodhyd.2004.12.004>
- Izydorczyk M.S., Macri L.J., MacGregor A.W., 1998. Structure and physicochemical properties of barley non-starch polysaccharides-II. Alkali-extractable β-glucans and arabinoxylans. *Carbohydr. Polym.*, 35, 259-269, [https://doi.org/10.1016/S0144-8617\(97\)00136-7](https://doi.org/10.1016/S0144-8617(97)00136-7)
- Mager M., Kiryluk J., Szmyt Z., Konieczna E., 2003. Methods to estimate a content of β-glucans in the products of barley grain milling by measuring the viscosity of their extracts (in Polish). *Food. Sci. Technol. Quality*, 4(37), 97-103.

- Svihus B., Edvardsen D.H., Bedford M.R., Gullord M., 2000. Effect of methods of analysis and heat treatment on viscosity of wheat, barley and oats. *Anim. Feed Sci. Technol.*, 88, 1-12, [https://doi.org/10.1016/S0377-8401\(00\)00213-3](https://doi.org/10.1016/S0377-8401(00)00213-3)
- Wood P.J., 2007. Cereal β -glucans in diet and health. *J. Cereal Sci.*, 46, 230-238, <https://doi.org/10.1016/j.jcs.2007.06.012>
- Zarzycki P., Sobota A., 2015. Effect of pH on apparent viscosity of wholemeal oat flour water dispersions. *Int. J. Food Prop.*, 18(2), 303-315, <https://doi.org/10.1080/10942912.2013.809538>
- Zhang D., Doehlert D.C., Moore W.R., 1997. Factors affecting viscosity of slurries of oat groat flours. *Cereal Chem.*, 74(6), 722-726, <https://doi.org/10.1094/CCHEM.1997.74.6.722>