Effects of process parameters on the properties of barley containing snacks enriched with brewer's spent grain

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Abstract Brewer's spent grain (BSG), a by-product of malting of barley in the production of malt extract, was used as an ingredient in extruded barley-based snacks in order to improve the nutritional value of the snacks and widen the applications of this by-product in food sector. The effects of the extrusion parameters on the selected properties of the snacks were studied. Snacks with different ingredients including whole grain barley flour, BSG, whey protein isolate (WPI), barley starch and waxy corn starch were produced in 5 separate trials using a co-rotating twin-screw extruder. Extrusion parameters were water content of the mass (17–23 %), screw speed (200–500 rpm) and temperature of the last section and die (110–150 °C). Expansion, hardness and water content of the snacks were determined. Snacks containing barley flour and BSG (10 % of solids) had small expansion and high hardness. Addition of WPI (20 % of solids) increased expansion only slightly. Snacks with high expansion and small hardness were obtained when part of the barley flour was replaced with starch (barley or waxy corn). Yet, the highest expansion and the smallest hardness were achieved when barley flour was used with barley starch and WPI without BSG. Furthermore, expansion increased by increasing screw speed and decreasing water content of the mass in most of the trials. This study showed that BSG is a suitable material for extruded snacks rich in dietary fiber. Physical properties of the snacks could be improved by using barley or waxy corn starch and WPI.

Keywords Snacks · Extrusion · Brewer's spent grain · Barley · Expansion

Introduction

Snacks are commonly produced by extrusion cooking technology, which is an efficient way to manufacture large amounts of products with porous structure (Matthey and Hanna 1997). The composition of the commercial snacks is generally not considered as healthy; they consist of mainly starch and fat. Yet, the consumption of snacks has increased, which can be risk for health. In order to improve the nutritional quality of snack products, their dietary fiber and protein content must be increased by selecting healthier ingredients. Whole grain flours could be favoured instead of endosperm flours and starch, and by-products such as brewer's spent grain (BSG) and whey proteins could be used as additives.

Barley, cereal cultivated widely in many countries including Finland, is mainly used for animal feed and for brewing industry. Even though snack products made of whole grain barley are not yet common, barley flour has been used in several extrusion studies (Altan et al. 2008a, b, c, 2009; Faraj et al. 2004; Huth et al. 2000; Kirjoranta et al. 2012; Vasanathan et al. 2002). BSG, a waste fraction of malting of barley, is a common by-product of the brewing industry (Mussato et al. 2006). It is a problematic product since it contains a lot of water (77–81 %), some fermentable sugars and enzyme activity (Mussato et al. 2006; Stojceska et al. 2008). That is why it must be stored at refrigerator temperature and used during a short period of time in order to avoid spoilage (Mussato et al. 2006). BSG is rich in dietary fiber and protein (about 70 and 20 % of solids, respectively) and it has a high mineral content (Mussato et al. 2006). The dietary fiber of BSG consists of water insoluble (lignin and cellulose) and

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water soluble (non-cellulosic polysaccharides, mostly arabinoxylans) dietary fiber. The content of dietary fiber in BSG may vary due to the malting process used. Approximate content of lignin is 28 %, cellulose 17 % and arabinoxylan 28 % of solids (Mussato et al. 2006). Because of the high dietary fiber and protein content, BSG could be useful ingredient for human foods with improved nutritional value. However, BSG is usually either thrown away or used as animal feed (Stojceska et al. 2008).

There are a few studies in which BSG has been used in extrudates (Ainsworth et al. 2007; Makowska et al. 2013; Stojceska et al. 2008, 2009). In those studies extrudates made of BSG were usually hard and not well expanded. More successfully BSG has been used in cookies (Kissell and Prentice 1979), in bread (Steinmacher et al. 2012) and in pasta (Sobukola et al. 2013) in order to increase the dietary fiber content of the products.

Whey proteins, by-products of the cheese industry, have high content of essential amino acids and minerals and they have good foaming and emulsifying properties (Matthey and Hanna 1997). In order to produce snacks with high protein content whey proteins have been previously used as additives in extruded snacks (Agbisit 2007; Allen et al. 2007; Brnčić et al. 2011; Cheng et al. 2007; Kirjoranta et al. 2012; Matthey and Hanna 1997; Onwulata et al. 1998, 2001a, b; Onwulata and Konstance 2006; Taylor et al. 2006). However, there are no published studies, in which whey proteins have been used together with BSG and whole grain barley flour.

The aims of this study were to prepare extrudates containing whole grain barley flour, BSG and whey protein isolate (WPI), and investigate the effects of extrusion process parameters (water content of the mass, screw speed and temperature profile) on the properties (water content, expansion and hardness) of the extrudates. It has been reported (e.g., Robin et al. 2012) that high contents of dietary fiber and protein may affect the structure of extruded snacks by reducing the expansion. That is why part of the barley flour was replaced with barley starch and waxy corn starch in some trials. A trial without BSG was also performed and used as a reference.

Materials and methods

Materials

Ingredients used in the extrusion trials were whole grain barley flour (Mylly-Matti, Helsinki Mills Ltd., Finland), brewer's spent grain from the production of barley malt extract (BSG; Laihia Mallas Ltd., Finland), barley starch (Altia Ltd., Finland), waxy corn starch (Roquette Freres, France) and whey protein isolate (WPI; Isolate Whey 90 Instant, Armor proteines, France). BSG was first freeze-dried (CHRIST Epsilon 2–25, Martin Christ Gefriertrocknungsanlagen

GmbH, Germany) at VTT Technical Research Centre of Finland and then milled (Retsch ZM 200, Ultra Centrifugal Mill, 12,000 rpm, GmbH, Germany) into particle size of less than 500 µm. Mass fractions of the powdery ingredients in different trials are shown in Table 1.

Barley flour contained 10.5 % protein, 69.6 % starch, 12.1 % dietary fiber and 3.5 % β -glucan of solids. BSG contained 57 % dietary fiber (26 % lignin, 16 % cellulose, 10 % hemicelluloses and 0.3 % β -glucan), 27 % protein, 10 % lipids, 2.3 % starch and 2.9 % ash of solids. Barley starch contained 91 % starch (26 % amylose and 74 % amylopectin), 8 % water, less than 0.5 % protein and less than 0.6 % lipids and waxy corn starch contained amylopectin 98 % and amylose 2 %. The protein content of WPI was more than 90 %, and it contained <3 % lactose, < 2 % lipids and <6 % water. Other ingredients used were distilled water and table salt (NaCl, Meira Ltd., Finland).

Water contents of the ingredients were determined by drying at 130 °C for 1 h in an oven (Termaks, Norway), except water content of WPI, which was determined using a vacuum incubator (Salvis Vacucenter VC 50, Salvis AG, Switzerland) at 70 °C for 5 h, and 1 h in a vacuum desiccator over phosphorus pentoxide (P₂O₅, pro-analyti, Merck, Germany). The weight loss was measured by using an analytical balance (Precisa 92SM-202A, Teopal, Switzerland). Water contents of the ingredients were taken into account in the calculation of the composition of the masses. Before extrusion powdery ingredients were mixed together using a mixer (Metabo, Germany) and salt was dissolved into distilled water to get it evenly distributed to the mass. In order to obtain constant salt content (1.0 % of solids) in the extruded mass with different water contents of the

Table 1 Mass fractions of the powdery ingredients (of solids) in the extrusion trials

	1 Barley- BSG	2 Barley- WPI- BSG	3 Barley-barley starch-WPI- BSG	4 Barley- barley starch- WPI	5 Barley-waxy corn starch- WPI-BSG
Barley flour	0.89	0.69	0.345	0.395	0.345
Barley starch	–	–	0.345	0.395	–
Waxy corn starch	–	–	–	–	0.345
WPI	–	0.20	0.20	0.20	0.20
BSG	0.10	0.10	0.10	–	0.10
Salt	0.01	0.01	0.01	0.01	0.01

WPI = whey protein isolate, BSG = brewer's spent grain

masses, 3 salt-water solutions with different concentrations were prepared.

Extrusion trials

Five separate extrusion trials were carried out using a co-rotating twin-screw extruder (Thermo Prism PTW24, Thermo Haake, PolyLab System, Germany). The length of the screws was 672 mm and diameter 24 mm, thus, giving L/D ratio of 28:1. The extruder consisted of 7 sections (length of each was 96 mm), 6 of which had an individual temperature control. The diameter of the heatable circular die was 5 mm. The temperature profile used in this study was: no warming (section 0), 40 (section 1), 70 (section 2), 70 (section 3), 100 (section 4), 110 (section 5) and 110/130/150 °C (section 6 and die). Powdery and liquid ingredients were fed separately to the extruder. Total mass flow into the extruder was constant, 67 g/min (4.02 kg/h). Box-Behnken's experimental design with 3 variables: water content of the mass (x_1 ; 17, 20 and 23 %), screw speed (x_2 ; 200, 350 and 500 rpm) and temperature of section 6 and die (x_3 ; 110, 130 and 150 °C), was used in trials 1–4 (Table 1). Trial number 4 did not contain BSG and it was therefore used as a reference. Experimental design consisted of 15 experiments including 3 repetitions in the middle point. Coded values (−1, 0, 1) were used in the calculation of the statistical models. The trial with waxy corn starch (trial number 5) was carried out using water content of the mass 17 %, screw speed 500 rpm and temperature of section 6 and die 130 °C, and it was conducted to find out if there was any difference between addition of barley starch and waxy corn starch.

Torque, specific mechanical energy and pressure at the die

During the extrusion, data of torque and pressure at the die was collected and sample extrudates were taken from the different experiments for the analyses. Based on the extrusion data, specific mechanical energy (SME) for each experiment of the trials was calculated according to Altan et al. (2008a, b, 2009) using the equation (1).

$$SME \text{ (Wh/kg)} = \frac{\text{Screw speed (rpm)} \cdot \text{Torque (Nm)}}{\text{Mass flow (kg/h)}} \quad (1)$$

Expansion

Expansion was calculated by measuring the diameter of 10 replicate extrudates of each experiment by a vernier

caliper and using the equation (2) and reported as an average of replicate measurements.

$$\text{Expansion (\%)} = \frac{\text{Diameter of extrudate (mm)} - \text{Diameter of die (mm)}}{\text{Diameter of die (mm)}} \cdot 100\% \quad (2)$$

Hardness

Extrudates were dried in a vacuum incubator (Salvis Vacucenter VC 50, Salvis AG, Switzerland) at 50 °C for 2–3 days before the hardness measurements in order to avoid the plasticization effect of water and to get comparable results. Hardness was determined by a universal testing machine (Instron 4465, High Wycombe, England) equipped with a 100 N load cell using a three-point bending test. Extrudates were pressed with an aluminum rectangular cross head (width of 29 mm and thickness of 3 mm) with a constant rate of 5 mm/min, and the force resisting the movement was recorded. Based on the measured force values, a linear trendline was fitted in the beginning of the data in which force (N) was shown as a function of distance (mm). The slope represented the value of the hardness (N/mm) of the extrudates, and it was reported as an average of 5 measurements.

Water content

Water contents of the extrudates were determined by vacuum-drying (50 °C for 2–3 days). After the drying, the samples were cooled 1 h in a vacuum desiccator over P₂O₅ before weighing the dry weight.

Statistical analyses

Regression models were fitted to the data and response surface plots were made by using Matlab (R2007b, The MathWorks, USA). Correlations between the response variables (torque, SME, pressure at the die, water content of the extrudates, expansion and hardness) were calculated by using Microsoft Excel.

Results and discussion

Properties of the extrudates

Expansion varied in different trials and experiments being 1–181 %, from which the lowest expansions were obtained in barley-BSG trial (Figs. 1 and 2). Possibly high content of water insoluble dietary fiber in BSG

Fig. 1 Images of the extrudates. From left to right: extrudates from barley-BSG, barley-WPI-BSG, barley-barley starch-WPI-BSG and barley-barley starch-WPI trial prepared with water content of the mass of 17 %, screw speed of 500 rpm and temperature of the section 6 and die of 130 °C

such as lignin and cellulose affected the air bubble formation and growth and caused low expansion (Robin et al. 2012). Similar results were obtained in previous

studies (Ainsworth et al. 2007; Stojceska et al. 2008, 2009). According to Stojceska et al. (2008) BSG could be added up to 20 % when it was mixed with corn starch in order to obtain commercially acceptable snacks. There are also other studies in which addition of water insoluble dietary fiber decreased expansion of extrudates. Yanniotis et al. (2007) reported that addition of water insoluble wheat fiber decreased the expansion of extrudates made of corn starch. Addition of corn bran, which contained mostly water insoluble dietary fiber, decreased expansion of corn flour extrudates in the study of Mendonca et al. (2000). However, corn bran could be added up to 25 % of solids in order to obtain snacks with good sensory properties. Addition of jatoba flour and cassava bran, which contain mostly water insoluble dietary fiber, decreased expansion of extrudates made of cassava starch (Chang et al. 1998; Hashimoto and Grossmann 2003). In the present study

Fig. 2 Response surface plots of expansion of A: Barley-BSG; B: Barley-WPI-BSG; C: Barley-barley starch-WPI-BSG; D: barley-barley starch-WPI as a function of the extrusion process parameters

the main ingredient was whole grain barley flour which has also been reported to create low expansion because of the high dietary fiber content (Kirjoranta et al. 2012; Köksel et al. 2004).

Addition of WPI and starch (barley or waxy corn) increased the expansion of extrudates containing BSG. Yet, extrudates without BSG had the highest expansion (Figs. 1 and 2). When structures of barley extrudates were studied using x-ray tomography, increased porosity and decreased thickness of the walls of the air bubbles were found with addition of WPI (Kirjoranta et al. 2012; Penttilä et al. 2011). Whey proteins are able to form foams and emulsions (Matthey and Hanna 1997). Thus, it could be speculated that WPI strengthened the walls around the air bubbles making the walls more elastic allowing air to be entrapped inside, while water insoluble fibers broke these walls and released the air bubbles. Addition of WPI increased expansion also in the studies of Agbisit (2007) and Kirjoranta et al. (2012). On the

contrary, in the studies of Matthey and Hanna (1997); Onwulata et al. (1998, 2001) and Allen et al. (2007) addition of whey protein concentrate (WPC) decreased expansion of extrudates. It has been speculated that other components in WPC, such as lactose, caused low expansion (Onwulata et al. 2001). However, when whey proteins were used together with water soluble dietary fiber, expansion increased (Kirjoranta et al. 2012; Onwulata et al. 2001).

Based on the regression models and response surface plots expansion was significantly increased by increasing screw speed in all trials (Table 2; Fig. 2). The effect of screw speed on expansion is well known and it has been reported by several researchers (Ainsworth et al. 2007; Baik et al. 2004; Chang et al. 1998; Cheng et al. 2007; Hashimoto and Grossmann 2003; Kirjoranta et al. 2012; Mezreb et al. 2003; Onwulata et al. 1998, 2001; Sharma and Gujral 2013).

Expansion increased by decreasing water content of the mass in all trials excluding barley-BSG trial (Table 2;

Table 2 Regression models. Coefficients of parameter estimates from the regression models for the properties of the extrudates (expansion, hardness and water content) and for torque, specific mechanical energy

(SME) and pressure at the die. Models calculated by using the coded values of variables (X_1 = water content of the mass, X_2 = screw speed, X_3 = temperature of the last section and die)

Response variable	Trial	X_1	X_2	X_3	$X_1 X_2$	$X_1 X_3$	$X_2 X_3$	Intercept	R^2	Lack of fit (p)
Expansion (%)	Barley-BSG	-0.5	+8.4***	+1	+1.8	+4.8*	-1.5	+16***	88.7	0.37
	Barley-WPI-BSG	-7**	+10***	-9.4**	-5.8	+9.3*	-5.5	+17***	90.8	0.21
	Barley-starch-WPI-BSG	-16***	+22***	-10	ns	ns	ns	+61***	91.7	0.06
	Barley-starch-WPI	-31***	+21***	-15**	ns	ns	ns	+122***	87.8	0.22
Hardness (N/mm)	Barley-BSG	-5	-31*	+39*	ns	ns	ns	+274***	53.6	0.21
	Barley-WPI-BSG	+30	-25	+30	ns	ns	ns	+205***	41.5 ^a	0.13
	Barley-starch-WPI-BSG	+20*	-70***	-5	ns	ns	ns	+145***	89.9	0.37
	Barley-starch-WPI	+24*	-36**	-13	+28	-5	+40*	+103	79.9	0.25
Water content (%) ^b	Barley-BSG	+2.8***	-0.4	-0.9**	ns	ns	ns	+16.0***	91.1	0.80
	Barley-WPI-BSG	+3.0***	-0.6**	-0.1	ns	ns	ns	+13.9	95.4	0.28
	Barley-starch-WPI-BSG	+3.0***	-0.6**	+0.03	ns	ns	ns	12.9***	97.2	0.36
Torque (Nm)	Barley-BSG	-2.3***	-2.8***	-0.8*	ns	ns	ns	+41***	92.5	0.70
	Barley-WPI-BSG	-0.6	-7***	-3*	-0.3	+4*	-0.3	+41***	86.1	0.07
	Barley-starch-WPI-BSG	+0.6	-6.9***	-3.3**	ns	ns	ns	+40***	90.4	0.22
	Barley-starch-WPI	+0.1	-6.4***	-3.3**	-3.8*	-2	-1.5	+45***	92.1	0.87
SME (Wh kg ⁻¹)	Barley-BSG	-3.3***	+10.1**	-0.9*	-1*	+0.5	-0.3	+31***	99.4	0.85
	Barley-WPI-BSG	-1	+16***	-4.8**	-1	+5.5*	-1.5	+57***	95.3	0.11
	Barley-starch-WPI-BSG	+0.5	+15.5***	-4.8***	ns	ns	ns	+55***	96.6	0.32
	Barley-starch-WPI	-1	+19***	-5*	-6*	-3	-4	+63***	93.8	0.54
Pressure at the die (bar)	Barley-BSG	-9**	-3	+1.4	ns	ns	ns	+33**	57.9	0.47
	Barley-WPI-BSG	-18***	-6***	-11***	+2.8	+3.0	+3.3*	+48***	98.5	0.03*
	Barley-starch-WPI-BSG	-15***	-11***	-7**	ns	ns	ns	+51***	92.2	0.30
	Barley-starch-WPI	-16***	-14***	-12**	ns	ns	ns	+54***	87.5	0.03*

^a low R^2 value and not significant p-value for regression (0.2), thus the model is not considered reliable

^b Water contents of extrudates in trial Barley-starch-WPI were incorrect and left out of the modelling

Significant at * $p < 0.05$, ** $p < 0.01$ and *** $p < 0.001$

ns = not significant

Fig. 2). Decreasing water content of the mass increased expansion of extrudates also in some previous studies (Ding et al. 2005; Kirjoranta et al. 2012; Ryu and Ng 2001; Sharma and Gujral 2013; Stojceska et al. 2009). According to Stojceska et al. (2009) shear stress and viscosity of mass were increased by decreasing water content of the mass, which caused higher expansion.

Expansion increased by decreasing temperature in barley-WPI-BSG and barley-barley starch-WPI trials (Table 2). Interaction between water content of the mass and temperature was found in barley-BSG and barley-WPI-BSG trials (Table 2; Fig. 2) which could also be seen from the curved surface of the response surface plots. High degree of starch gelatinization is usually needed for high expansion (Yanniotis et al. 2007). Sharma and Gujral (2013) observed that gelatinization of starch increased when water content of the mass and extrusion temperature increased. In their study water content ranged from 15 to 20 %, temperature varied in sections 3–4 (125–150 and 140–180 °C, respectively) but screw speed was kept constant (400 rpm). In addition, Ibanoglu et al. (1996) reported that high degree of gelatinization of starch could be achieved when high temperature was used together with high screw speed (300 rpm). Temperature was varied in the whole extrusion barrel and tested temperatures were relatively low (60, 90 and 120 °C). However, expansion did not increase by increasing temperature in the present study in which expansion was mostly affected by water content of the mass and screw speed. Similarly, high extrusion temperature was found to decrease viscosity, shear, SME and expansion in the study of Köksel et al. (2004) in which tested extrusion temperatures of the last section and die were 120–160 °C and 130–170 °C, respectively.

Hardness varied in different trials and experiments between 30 and 380 N/mm where barley-BSG extrudates had the highest hardness. Addition of WPI with or without starch decreased the hardness of extrudates containing BSG, effect of which was higher with waxy corn starch than with barley starch. However, the smallest hardness was achieved without

BSG. Based on the regression analysis, hardness increased with increasing water content of the mass and decreasing screw speed in barley-barley starch-WPI-BSG and in barley-barley starch-WPI trials (Table 2). In barley-BSG trial hardness increased with increasing temperature (Table 2). Interaction between screw speed and temperature was found in barley-barley starch-WPI trial (Table 2). There was also a significant negative correlation between expansion and hardness except in barley-BSG trial (Table 4).

In the present study, the highest expansion and the lowest hardness of extrudates containing BSG were obtained with addition of waxy corn starch. Similarly, extrudates made of waxy corn starch had higher expansion and smaller hardness than extrudates made of regular corn starch (Allen et al. 2007; Matthey and Hanna 1997). Waxy starch contains mostly amylopectin which is a branched molecule whereas regular starch contains also amylose (ca. 26 %), which has a mainly linear structure (Moraru and Kokini 2003). It has been suggested that linear amylose molecules may align themselves or form complexes with other molecules such as whey proteins by hydrogen bonds causing decrease in expansion and increase in hardness (Allen et al. 2007; Matthey and Hanna 1997). On the contrary, with waxy starch, protein-protein interactions are favoured instead, which is found to increase expansion and decrease hardness (Allen et al. 2007; Matthey and Hanna 1997).

The chemical composition calculated from the ingredients showed that barley-BSG snacks with or without WPI contained 14 and 17 % dietary fiber and 28 and 12 % protein, respectively (Table 3) which can be considered as higher contents than usually found in conventional snacks. However, the hardness of those snacks was so high that probably those products would not be acceptable for consumers. In comparison, commercial corn snack measured by the same method as in the present study had hardness of 2.7 N/mm (Kirjoranta et al. 2012). When part of the barley flour was replaced with starch, particularly with waxy corn starch, hardness decreased to an acceptable level. Furthermore, the snacks contained

Table 3 Calculated composition (% of solids) and the highest expansion and the lowest hardness of extrudates from different trials

Trial	Starch (%)	Dietary fiber (%)	Protein (%)	Lipids (%)	The highest expansion (%)	The lowest hardness (N/mm)
1 Barley-BSG	63	17	12	3	27 ± 4	200 ± 50
2 Barley-WPI-BSG	49	14	28	3	47 ± 6	100 ± 10
3 Barley-barley starch-WPI-BSG	68	10	25	2	107 ± 4	70 ± 20
4 Barley-barley starch-WPI	74	5	23	1	181 ± 4	35 ± 20
5 Barley-waxy corn starch-WPI-BSG	68	10	25	2	122 ± 6	54 ± 20

Extrusion parameters: water content of the mass 17 %, screw speed 500 rpm, temperature of section 6 and die 130 °C

more than 6 % dietary fiber and they could be marked as high dietary fiber food (Robin et al. 2012).

Water content of the extrudates varied depending on the trial and the experiment being 8.4–18.2 %. Water content of BSG containing extrudates was found to be lower when WPI was added with or without starch. As it was expected, water content of the extrudates increased by increasing water content of the mass (Table 2). Decreasing screw speed increased water content of the extrudates in barley-WPI-BSG and in barley-starch-WPI-BSG trials and decreasing temperature increased water content of extrudates in barley-BSG trial (Table 2).

Response variables from the extrusion process

Torque varied in different extrusion trials and experiments from 19 Nm to 54 Nm being the lowest in barley-BSG trial. Decreasing screw speed and temperature increased torque in all trials (Table 2). Torque increased by decreasing water content of the mass only in barley-BSG trial (Table 2). However, there was a significant interaction between water content of the mass and temperature in barley-WPI-BSG trial and between water content of the mass and screw speed in barley-barley starch-WPI trial (Table 2).

Specific mechanical energy (SME) was 19–91 Whkg⁻¹ depending on the trial and experiment. The lowest SME values were found in barley-BSG trial. Addition of WPI with

or without starch caused higher SME. SME increased with increasing screw speed and decreasing temperature in all trials and increased by decreasing water content of the mass in barley-BSG trial (Table 2). Interaction between water content of the mass and screw speed was found in barley-BSG and barley-starch-WPI trials and interaction between water content of the mass and temperature was found in barley-WPI-BSG trial (Table 2). Addition of WPI caused possibly more shear forces which could be seen from the increased SME values. Increased shear stress could be due to increased viscosity of the mass, since proteins are capable of binding water (Onwulata et al. 2001). At low water contents of the mass, high shear stress increases gelatinization of starch which is needed to obtain expanded extrudates (e.g., Köksel et al. 2004). High SME has been reported to increase expansion (Kirjoranta et al. 2012; Matthey and Hanna 1997; Onwulata et al. 2001; Ryu and Ng 2001). In fact, in the present study, a positive correlation between SME and expansion was found in all the trials (Table 4).

Pressure at the die varied being 22–54 bar. Addition of WPI with or without starch seemed to increase pressure. Decreasing water content of the mass increased the pressure in all trials and decreasing screw speed increased pressure in all trials with the exception of barley-BSG trial (Table 2). Moreover, pressure increased with decreasing temperature in barley-WPI-BSG and in barley-starch-WPI trials (Table 2). Interaction between screw speed and temperature was found

Table 4 Coefficients of correlation between the response variables. Significant correlations ($p < 0.05$) are **bolded**

		SME	Pressure	Water content	Expansion	Hardness
Barley-BSG	Torque	-0.439	0.654	-0.487	-0.561	0.456
	SME		-0.029	-0.396	0.805	-0.385
	Pressure			-0.637	-0.315	-0.072
	Water content				-0.192	0.181
	Expansion					-0.401
Barley-WPI-BSG	Torque	-0.482	0.466	0.049	-0.029	0.075
	SME		-0.068	-0.246	0.769	-0.407
	Pressure			-0.722	0.421	-0.474
	Water content				-0.505	0.525
	Expansion					-0.693
Barley-barley starch-WPI-BSG	Torque	-0.663	0.565	0.216	-0.536	0.864
	SME		-0.428	-0.180	0.795	-0.823
	Pressure			-0.614	0.115	0.311
	Water content				-0.673	0.419
	Expansion					-0.804
Barley-barley starch-WPI	Torque	-0.440	0.525	nd	-0.274	0.451
	SME		-0.412	nd	0.585	-0.586
	Pressure			nd	0.293	0.273
	Water content				nd	nd
	Expansion					-0.615

nd = no data

in barley-WPI-BSG trial (Table 2). Even though die pressure has been reported to correlate with expansion (Hayter et al. 1986), a significant correlation between pressure at the die and expansion was not found in the present study.

Conclusions

BSG could be used as an ingredient in barley-based extruded snacks which contained high amount of dietary fiber and protein. However, barley-BSG extrudates were hard and poorly expanded possibly due to the high amount of water insoluble dietary fiber (lignin and cellulose) in BSG and whole grain barley flour. Structure could be improved by adding WPI and starch (barley or waxy corn starch). With addition of waxy corn starch (34.5 %) and WPI (20 %), the properties of extrudates containing BSG (10 %) were quite close to the properties of barley-barley starch-WPI extrudates (without BSG). Furthermore, properties of the extrudates such as expansion and hardness could be affected by the extrusion process parameters. In most trials increasing screw speed and decreasing water content of the mass increased expansion and decreased hardness. In order to get highly expanded extrudates containing BSG without adding starch, BSG could be treated enzymatically to solubilise part of the insoluble dietary fiber in BSG. Milling of BSG into smaller particle size might also be a way to get higher expansion of extrudates containing BSG.

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References

- Agbisit RMN (2007) Relationships between material properties and microstructure-mechanical attributes of extruded biopolymeric foams. [DPhil dissertation]. Manhattan, Kansas: Kansas State Univ. 91p. Available from: UMI Microform 3292473.
- Ainsworth P, İbanoglu Ş, Plunkett A, İbanoglu E, Stojceska V (2007) Effect of brewers spent grain addition and screw speed on the selected physical and nutritional properties of an extruded snack. *J Food Eng* 81:702–709
- Allen KE, Carpenter CE, Walsh MK (2007) Influence of protein level and starch type on an extrusion-expanded whey product. *Int J Food Sci Tech* 42:953–960
- Altan A, McCarthy KL, Maskan M (2008a) Evaluation of snack foods from barley-tomato pomace blends by extrusion processing. *J Food Eng* 84:231–242
- Altan A, McCarthy KL, Maskan M (2008b) Extrusion cooking of barley flour and process parameter optimization by using response surface methodology. *J Sci Food Agric* 88:1648–1659
- Altan A, McCarthy KL, Maskan M (2008c) Twin-screw extrusion of barley-grape pomace blends: extrudate characteristics and determination of optimum processing conditions. *J Food Eng* 89:24–32
- Altan A, McCarthy KL, Maskan M (2009) Effect of screw configuration and raw material on some properties of barley extrudates. *J Food Eng* 92:377–382
- Baik BK, Powers J, Nguyen LT (2004) Extrusion of regular and waxy barley flours for production of expanded cereals. *Cereal Chem* 81: 94–99
- Brnčić M, Bosiljkov T, Ukrainczyk M, Tripalo B, Brnčić SR, Karlović S, Karlović D, Ježek D, Topić DV (2011) Influence of whey protein addition and feed moisture content on chosen physicochemical properties of directly expanded corn extrudates. *Food Bioprocess Technol* 4:1296–1306
- Chang YK, Silva MR, Gutkoski LC, Sebio L, Da Silva MAAP (1998) Development of extruded snacks using jatobá (*Hymenaea stigonocarpa* mart) flour and cassava starch blends. *J Sci Food Agric* 78:59–66
- Cheng EM, Alavi S, Pearson T, Agbisit R (2007) Mechanical-acoustic and sensory evaluations of cornstarch-whey protein isolate extrudates. *J Texture Stud* 38:473–498
- Ding QB, Ainsworth P, Tucker G, Marson H (2005) The effect of extrusion conditions on the physicochemical properties and sensory characteristics of rice-based expanded snacks. *J Food Eng* 66:283–289
- Faraj A, Vasanthan T, Hoover R (2004) The effect of extrusion cooking on resistant starch formation in waxy and regular barley flours. *Food Res Int* 37:515–525
- Hashimoto JM, Grossmann MV (2003) Effects of extrusion conditions on quality of cassava bran / cassava starch extrudates. *Int J Food Sci Tech* 38:511–517
- Hayter AL, Smith AC, Richmond P (1986) The physical properties of extruded food foams. *J Mater Sci* 21:3729–3736
- Huth M, Dongowski G, Gebhardt E, Flammé W (2000) Functional properties of dietary fibre enriched extrudates from barley. *J Cereal Sci* 32:115–128
- Ibanoglu S, Ainsworth P, Hayes GD (1996) Extrusion of tarhana: effect of operating variables on starch gelatinization. *Food Chem* 57:541–544
- Kirjoranta S, Solala K, Suuronen JP, Penttilä P, Peura M, Serimaa R, Tenkanen M, Jouppila K (2012) Effects of process variables and addition of polydextrose and whey protein isolate on the properties of barley extrudates. *Int J Food Sci Tech* 47:1165–1175
- Kissell LT, Prentice N (1979) Protein and fiber enrichment of cookie flour with brewer's spent grain. *Cereal Chem* 56:261–266
- Köksel H, Ryu GH, Başman A, Demiralp H, Ng PKW (2004) Effects of extrusion variables on the properties of waxy hullless barley extrudates. *Nahrung/Food* 48:19–24.
- Makowska A, Mildner-Szkudlarz S, Obuchowski W (2013) Effect of brewer's spent grain addition on properties of corn extrudates with an increased dietary fiber content. *Pol J Food Nutr Sci* 63:19–23
- Matthey FP, Hanna MA (1997) Physical and functional properties of twin-screw extruded whey protein concentrate-corn starch blends. *LWT* 30:359–366
- Mendonça S, Grossmann MVE, Verhé R (2000) Corn bran as a fiber source in expanded snacks. *LWT* 33:2–8
- Mezreb K, Goullieux A, Ralainirina R, Queneudec M (2003) Application of image analysis to measure screw speed influence on physical properties of corn and wheat extrudates. *J Food Eng* 57:145–152
- Moraru CI, Kokini JL (2003) Nucleation and expansion during extrusion and microwave heating of cereal foods. *Crrfs* 2:120–138.
- Mussato SI, Dragone G, Roberto IC (2006) Brewers' spent grain: generation, characteristics and potential applications (a review). *J Cereal Sci* 43:1–14
- Onwulata CI, Konstance RP (2006) Extruded corn meal and whey protein concentrate: effect of particle size. *J Food Process Pres* 30:475–487

- Onwulata CI, Konstance RP, Smith PW, Holsinger VH (1998) Physical properties of extruded products as affected by cheese whey. *J Food Sci* 63:1–5
- Onwulata CI, Konstance RP, Smith PW, Holsinger VH (2001a) Co-extrusion of dietary fiber and milk proteins in expanded corn products. *LWT* 34:424–429
- Onwulata CI, Smith PW, Konstance RP, Holsinger VH (2001b) Incorporation of whey products in extruded corn, potato, or rice snacks. *Food Res Int* 34:679–687
- Penttilä P, Suuronen JP, Kirjoranta S, Peura M, Jouppila K, Tenkanen M, Serimaa R (2011) X-ray characterization of starch-based solid foams. *J Mat Sci* 46:3470–3479
- Robin F, Schuchmann HP, Palzer S (2012) Dietary fiber in extruded cereals: limitations and opportunities. *Trends Food Sci* 28:23–32
- Ryu GH, Ng PKW (2001) Effects of selected process parameters on expansion and mechanical properties of wheat flour and whole corn meal extrudates. *Starch / Stärke* 53:147–154
- Sharma P, Gujral HS (2013) Extrusion of hulled barley affecting β -glucan and properties of extrudates. *Food Bioprocess Technol* 6:1374–1389
- Sobukola OP, Babajide JM, Ogunsade O (2013) Effect of brewers spent grain addition and extrusion parameters on some properties of extruded yam starch-based pasta. *J Food Process Pres* 37:734–743
- Steinmacher NC, Honna FA, Gasparetto AV, Anibal D, Grossmann MVE (2012) Bioconversion of brewer's spent grains by reactive extrusion and their application in bread-making. *LWT* 46:542–547
- Stojceska V, Ainsworth P, Plunkett A, İbanoğlu S (2008) The recycling of brewer's processing by-product into ready-to-eat snacks using extrusion technology. *J Cereal Sci* 47:469–479
- Stojceska V, Ainsworth P, Plunkett A, İbanoğlu S (2009) The effect of extrusion cooking using different water feed rates on the quality of ready-to-eat snacks made from food by-products. *Food Chem* 114: 226–232
- Taylor DP, Carpenter CE, Walsh MK (2006) Influence of sulfonation on the properties of expanded extrudates containing 32 % whey protein. *J Food Sci* 71:17–24
- Vasanthan T, Gaosong J, Yeung J, Li J (2002) Dietary fiber profile of barley flour as affected by extrusion cooking. *Food Chem* 77:35–40
- Yanniotis S, Petraki A, Soumpasi E (2007) Effect of pectin and wheat fibers on quality attributes of extruded cornstarch. *J Food Eng* 80:594–599