Journal of Cereal Science xxx (2016) xxx-xxx

Contents lists available at ScienceDirect

Journal of Cereal Science

journal homepage: www.elsevier.com

Factors affecting structural properties and *in vitro* starch digestibility of extruded starchy foams containing bran

Syed Ariful Alam[a, b, *], Jenni Järvinen[a], Harri Kokkonen[c], Jukka Jurvelin[c], Kaisa Poutanen[a], Nesli Sozer[a, **]

[a] *VTT Technical Research Centre of Finland, Tietotie 2, FI-02150, Espoo, Finland*
[b] *Department of Food and Environmental Sciences, Agnes Sjöbergin katu 2, P.O. Box 66, 00014, University of Helsinki, Helsinki, Finland*
[c] *Department of Applied Physics, University of Eastern Finland, P.O. Box 1627, 70210, Kuopio, Finland*

ARTICLE INFO

Article history:
Received 19 November 2015
Received in revised form 20 June 2016
Accepted 28 August 2016
Available online xxx

Keywords:
Dietary fibre
Particle size reduction
Texture
Starch digestibility

ABSTRACT

Rye bran of two different particle sizes (coarse: 440 µm and fine: 28 µm) were prepared by milling of commercial rye bran. Coarse and fine rye bran was added into a blend of rye endosperm flour and corn starch (70:30) to achieve two bran levels, 15 or 30%, to produce directly puffed extrudates. A co-rotating twin screw extruder was used with a screw speed of 500 rpm, barrel temperature profile: 40-70-75-90-95-110-110 °C and constant feed rate of 67 g/min. Feed moisture content of 17% was used either as in barrel-water feed or as preconditioning. Fine bran addition effectively improved macrostructural properties as compared to coarse bran through increasing expansion by 3.3–11.7% and piece density by 3.8–10.5%. Reduction of bran particle size significantly ($P < 0.05$) increased crispiness by 66.7–203.3%. Particle size reduction of bran had only minor influences on cell wall thickness, cell area and hydrolysis index of the extrudates. Extrudates made with 30% fine bran at in barrel-water feed provided the crispiest extrudates with lower *in vitro* hydrolysis index. The results demonstrated that the macrostructural and mechanical properties of extrudates containing rye bran can be improved by reducing bran particle size.

Abbreviations

A_{uc}	Area under the curve
C_i	Crispiness index
C_w	Crispiness work
D	Average cell diameter
DF	Dietary fibre
GI	Glycaemic index
HI	Starch hydrolysis index
IB	In barrel-water feed
PC	Preconditioning
SDF	Soluble dietary fibre
t	Average cell wall thickness
TDF	Total dietary fibre
WAI	Water absorption index
WSI	Water solubility index
XMT	X-ray microtomography

1. Introduction

Rye is a key source of dietary fibre (DF) and the second most common grain after wheat used in bread production in Europe; however the use of rye in extruded snack products is limited. Snack foods are often made of refined flour and starch (corn, wheat, rice, oats and potato), and thus these products tend to be low in DF, protein and other essential nutrients (Robin et al., 2012). There is an increasing consumer demand for healthy convenience and snack foods with high DF content. Several studies have shown that consumption of DF reduces the risk of obesity, cardiovascular disease, cancer and diabetes (Smith and Tucker, 2011; Hauner et al., 2012).

Rye bran, a by-product generated during rye flour processing, consists of 38–48% DF, 14–18% protein and 13–28% starch, and therefore could be utilized as a low-cost fibre and protein source in healthy snack formulations (Alam et al., 2014). High GI (glycaemic index) foods such as starch based extruded products have been reported to associate with increasing health risks related to obesity, diabetes and coronary heart disease (Livesey et al., 2008). Thus snack products with low GI and high DF are of interest for consumers and consequently food manufacturers. Processing method, feed material composition, microstructure and textural properties of food influence starch digestibility (Singh et al., 2013). It is thus important to understand how physical, textural and microstructural properties of starchy snack foods supplemented with DF affect the digestibility of starch.

The properties of extruded products depend strongly on the raw materials, level of incorporation and the source of the DF and finally on the processing conditions (Altan and Maskan, 2011). High fibre extrusion is challenging, resulting often in highly dense, less crispy and hard textures, which are not appreciated by consumers (Robin et al., 2012; Sozer and Poutanen, 2013). Cereal fractions rich in insoluble DF have poor gas-holding capacity and interfere with the expansion of air cells (Singh et al., 2007). Addition of bran in starch based products interferes with the continuity of starchy matrix. This

* Corresponding author. VTT Technical Research Centre of Finland, Tietotie 2, FI-02150, Espoo, Finland.
** Corresponding author.
Email addresses: ariful.alam@vtt.fi (S.A. Alam); nesli.sozer@vtt.fi (N. Sozer)

http://dx.doi.org/10.1016/j.jcs.2016.08.018
0733-5210/

affects both structural and mechanical properties thus reducing the overall quality (Sozer and Poutanen, 2013).

Due to the adverse effect of cereal bran on product quality, typically only 10–32% of bran has been added in previous studies as reviewed by Robin et al. (2012) and Sozer and Poutanen (2013). Several researchers reported that more expanded, less hard and crispier extrudates could be obtained by decreasing the particle size of the feed material such as fibre and wholegrain (Lue et al., 1991; Mathew et al., 1999). To date, a number of studies have been conducted to determine the effect of insoluble fibre addition and particle size reduction on the structural and textural properties of extruded products with different fibre sources such as sugar beet fibre (Lue et al., 1991), oat-fibre and cellulose (Guan et al., 2004), wheat bran (Robin et al., 2011a; Santala et al., 2014), oat bran (Sibakov et al., 2014) and rye bran (Alam et al., 2014).

In our previous study (Alam et al., 2014) a decrease in rye bran particle size from 440 to 28 μm improved overall quality of 100% rye bran extrudates. Particle size reduction of wheat bran (702 → 84 μm) improved expansion but did not affect textural attributes when 20% wheat bran was added to rye flour based extrudates (Santala et al., 2014). Robin et al. (2011a) and Sibakov et al. (2014) observed no significant increase in degree of expansion by adding 12–24% wheat bran (317 → 224 μm) and 10% oat bran (213 → 32 μm) into wheat and defatted oat flour based extrudates, respectively. Therefore, effect of particle size reduction on structural and textural properties needs to be further evaluated through macro- (expansion), and micro-structural properties such as porosity and cell wall thickness. To the best of our knowledge literature is missing the effect of bran particle size reduction on *in vitro* starch digestibility of high fibre starchy extrudates. The aim of the current work was to understand the factors (eg. hydration regimen, dietary fibre content and particle size) effecting the structural properties and *in vitro* starch digestibility of starch-based rye bran-enriched extrudates.

2. Materials and methods

2.1. Feed material preparation

Native rye bran obtained from Fazer Mill and Mixes (Lahti, Finland) was milled to two different particle sizes, coarse and fine. Coarse (D_{50} = 440 μm) and fine (D_{50} = 28 μm) rye bran were prepared at VTT Technical Research Centre of Finland (Espoo, Finland) by milling native rye bran using a published protocol used in our previous study (Alam et al., 2014). Rye endosperm flour (with a DF content of 7%, carbohydrate of 75% and protein content of 6% as detailed in the manufacturer specifications) was obtained from Helsinki Mills Ltd., Järvenpää, Finland. Waxy corn starch with 97% of amylopectin was from Roquette Ltd., France and was used to make starch-flour mixture by adding 30% of starch into 70% of rye flour using a spiral mixer (Diosna SP 24 D, Dierks & Söhne, Osnabrück, Germany). This starch-flour mixture was used as extrusion feed together with coarse- or fine-particle sized rye bran so that the amount of bran was either 15% or 30% in the starch-flour-bran mixtures. Two different bran addition level categorises as low (15% bran: 82% starch and 8.2% DF) and high (30% bran: 74% starch and 12.6% DF) fibre feed material. Rye bran was mixed with starch-flour mixture prior to extrusion using the same spiral mixer to make the final blend of starch-flour-bran.

2.2. Particle size analyses

Particle size distribution of the milled raw materials was determined with a Laser Diffraction Particle Size Analyser (LDPSA) (Beckman Coulter LS 230, Coulter Corporation, Miami, USA) using the wet module. MilliQ-water was used as background solution. Particle size distributions were expressed in volume units and the measurements were made in duplicate.

2.3. Extrusion processing

A co-rotating twin-screw extruder (Poly Lab System, Thermo Prism PTW24, Thermo Haake, Dreieich, Germany) was used for extrusion trials using a method described by Alam et al. (2014). A full factorial experimental design was used for all extrusion trials (Table 1). The feed rate of 67 g/min, screw speed of 500 rpm and feed moisture of 17% were kept constant during the extrusion experiments. The barrel temperature profile was: 40, 70, 75, 90, 95, 110 and 110 °C in sections 1–6 and in the die. Two water addition regimens were used: in barrel–water feed (IB) and preconditioning (PC). Preconditioning was carried out by adjusting the moisture content of the bran-flour mixtures before extrusion using the protocol published by (Alam et al., 2014). The values of torque, die pressure and die temperature were monitored and recorded during the extrusion.

2.4. Macrostructural analyses

The extruded samples of each extrusion experiment were collected, dried at 105 °C for 20 min and cooled to room temperature. The measurements of expansion rate, specific length and piece density were made from 20 replicates from each extrusion treatments using the method described by Alam et al. (2014).

2.5. Microstructural analyses

In X-ray microtomography (XMT), the samples were analysed in triplicate using a method described by Alam et al. (2014). Each sample of 10 mm long pieces were scanned using a desk-top XMT system (Model 1172, SkyScan, Aartselaar, Belgium) to obtain the parameters of porosity, average cell wall thickness (t), average cell diameter (D) and average cell area. Average cell area was calculated using the formula (area = $(\pi/4) \times D^2$), where D represents average cell diameter.

Table 1
Experimental plan for product optimization.

Sample	Median particle size (μm)	Hydration regimen (IB/PC)	Bran (%)
Coarse IB 15%	440	IB	15
Coarse IB 30%	440	IB	30
Coarse PC 15%	440	PC	15
Coarse PC 30%	440	PC	30
Fine IB 15%	28	IB	15
Fine IB 30%	28	IB	30
Fine PC 15%	28	PC	15
Fine PC 30%	28	PC	30

Raw material concentration in feed based on dry mass (*IB* = in barrel–water feed, *PC* = preconditioning).

2.6. Characterization of textural properties

Textural properties of extrudates were analysed by the uniaxial compression test using a texture analyser (Texture Analyser TA-HDi, HD3071, Stable Micro Systems, United Kingdom) equipped with a 250 kg load cell and a cylindrical 36 mm aluminium probe using a protocol used by Alam et al. (2014). The samples (20 replicates for each experiment) were deformed at 70% strain with a test speed of 1 mm/s. Texture Exponent software v.5.1.2.0 (Stable Micro Systems, UK) was used to obtain values of hardness (F_{max}), crushing force, crispiness work (C_w) and crispiness index (C_i). The calculation was performed using the formulas published by Alam et al. (2014). High crispiness is accompanied by a high C_i and low C_w value, whereas low crispiness corresponds to a low C_i and high C_w value.

2.7. Starch hydrolysis index analyses

In vitro starch hydrolysis index (HI) was measured using a method described by Sozer et al. (2014). The ground extruded samples of about 2 g was used to obtain each starch hydrolysis curve. The area under the curve (A_{uc}) was obtained after 180 min incubation with porcine pancreatic α-amylase (Sigma-Aldrich Co. LLC, USA). The A_{uc} was calculated using Sigmaplot 10.0 (Systat Software Inc., Point Richmond, CA, USA) programme with the preloaded macros. HI values were calculated using the formula: HI = (A_{uc} of extrudates / Average A_{uc} of white wheat bread) × 100 and the results reported as mean ± SD. Whole grain rye bread and extrudates made of 100% coarse and fine rye bran was analysed as control sample.

2.8. Water absorption and water solubility analyses

Water absorption index (WAI) and water solubility index (WSI) were measured using a method described by Anderson et al. (1969) with modifications. WAI measures the amount of water absorbed by starch and WSI measures the amount of soluble components released from starch. Extruded samples were ground by centrifugal mill (Retsch ZM200, Haan, Germany) to pass through 250 μm sieves. Extruded samples of 2.5 g was suspended in 25 ml of deionized water and mixed shortly on a vortex mixer. Sample was hydrated for 30 min at room temperature using a planar-shaker (model B1, Edmund Buhler, Tübingen, Germany) and centrifuged (Heraeus Sepatech Biofuge 28RS, Heraeus, Osterode, Germany) at 3000 × g at room temperature for 10 min. The supernatant was separated and the weight of sediment was obtained. The amount of dissolved solids was determined by drying the supernatant at 130 °C for 3 h and by obtaining the weight of dried sample. Measurements were made in triplicate.

Water absorption index (WAI) was calculated as follows:

$$WAI = \frac{m_\beta}{m_\alpha} \times 100$$

where m_β is the weight of the sediment (in gram, g) and m_α is the weight of the sample (g).

Water solubility index (WSI) was calculated:

$$WSI = \frac{m_\gamma}{m_a} \times 100$$

where m_γ is the weight of the dissolved solids in supernatant (g) and m_a is the weight of the sample (g).

2.9. Statistical analyses

Statistical significance was assessed by one-way ANOVA (Tukey's honest significant difference (HSD)) using a significance level of 0.05. Linear correlations between different variables were calculated using 2-tailed Pearson bivariate correlation with significance levels of 0.01 and 0.05. Statistical analyses were made using SPSS Statistics 20 (SPSS Inc., Chicago, USA) software.

3. Results and discussion

3.1. Macrostructure

Decrease in bran particle size from 440 to 28 μm increased expansion rate but decreased specific length and piece density of rye bran enriched starch based extrudates. Expansion rate ranged between 281% and 323% and density from 187 kg/m^3 to 229 kg/m^3 and negatively correlated with each other ($r = -0.88$, $P < 0.01$) (Fig. 1 and Table 3). This is in agreement with previous literature where particle size reduction of corn bran (Pai et al., 2009), sugar beet fibre (Lue et al., 1991) and rye bran (Alam et al., 2014) resulted in significant increases in expansion. There was significant positive correlation ($r = 0.74$, $P < 0.05$) between the particle size and specific length. Specific length varied from 25.7 to 30.6 m/kg and showed a negative correlation ($r = -0.83$, $P < 0.05$) with expansion rate indicating that the expansion rate increased with decreasing specific length (Fig. 1). A significant negative correlation ($r = -0.81$, $P < 0.05$) between the particle size and expansion rate indicating that the higher the bran particle size the lower the radial expansion, which is in agreement with the study of Santala et al. (2014) of wheat bran extrudates. As part of the starch is replaced by bran particles, the extensibility of the melt in the radial direction is reduced. Bran particles align longitudinally due to the shear in the extruder and hinder radial expansion, which would be against the orientation of the fibres and cause rupture of the cells. Thus, radial expansion decreases and is compensated with longitudinal expansion.

Increase in bran content from 15% to 30% decreased expansion and increased piece density significantly ($p < 0.05$). Addition of bran (e.g. wheat, corn and oat) or other fibre sources (e.g. apple pomace) has often been reported to decrease expansion rate and increase density and specific length (Brennan et al., 2008; Robin et al., 2012; Sibakov et al., 2014). It is believed that above a critical concentration (10–15%), fibres start to interfere with the continuous structure of the melt and prevent its elastic deformation and reduce gas holding capacity during expansion (Sozer and Poutanen, 2013). A recent study by Chanvrier et al. (2014) reported a significant loss of expansion to occur only when more than 20% wheat and oat bran were added into whole wheat and corn based recipes.

A pronounced effect of pre-conditioning on expansion rate was observed particularly for fine-particle sized bran at 30% addition level. Preconditioning gave more expanded extrudates as compared to in-barrel water fed samples (IB). Liu et al. (2011) mentioned that typically a higher IB water addition resulted in lower expansion. This is related to reduction of melt viscosity by decreasing the temperature which corresponds to more cell collapse. However, effect of hydration regimen on expansion was rather complex for coarse-particle sized bran; a reduced expansion was found for pre-conditioned samples. It could be assumed that coarse-particle sized bran had greater

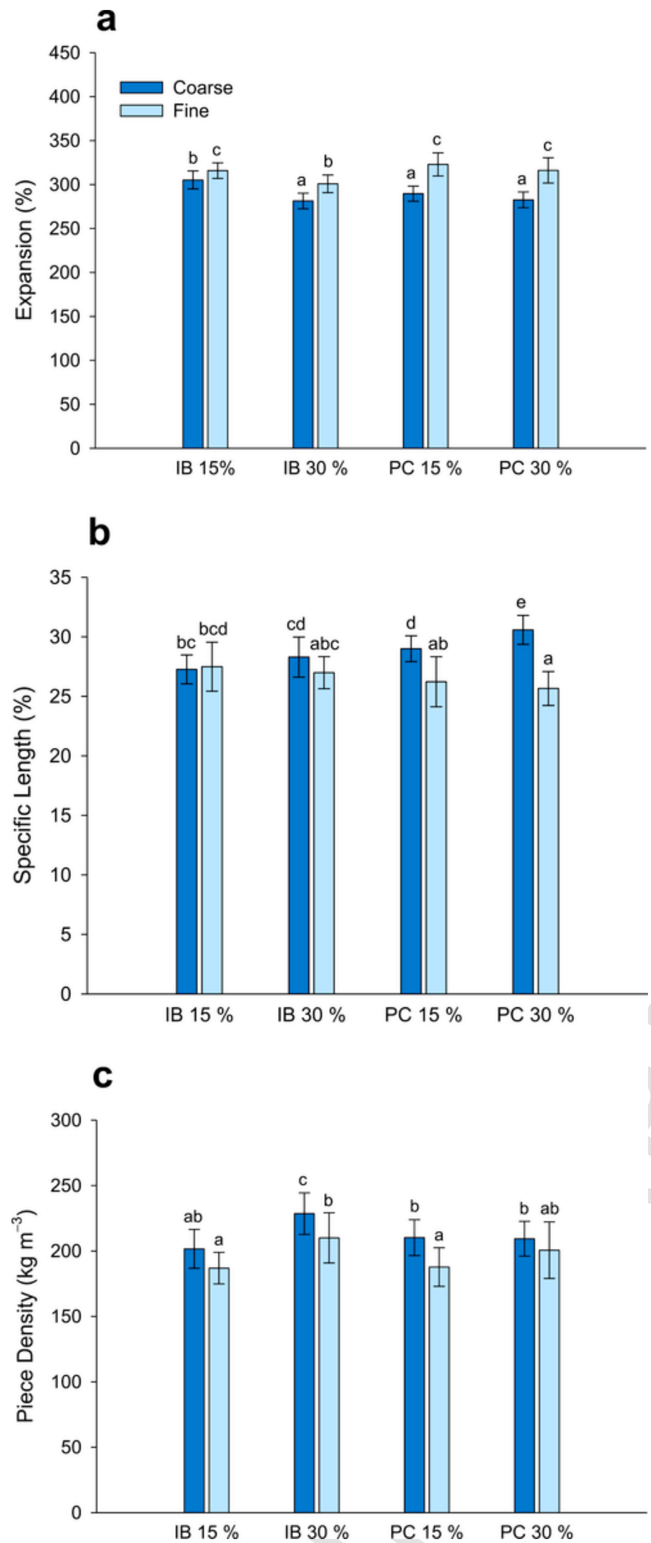


Fig. 1. a) Expansion, **b)** specific length and **c)** piece density of the extrudates made with coarse-, and fine-particle-sized of rye bran (15% and 30% inclusion) processed with 17% feed moisture in two different hydration regimens (*IB* in barrel–water feed, *PC* preconditioning) at 500 rpm and at 110 °C. Bars followed by the **same letters** in **each figure** were **not** significantly different ($P < 0.05$).

water binding capacity and bound more water during preconditioning and thus reduced the amount of water available for expansion.

3.2. Microstructure

Microstructural properties were studied by x-ray microtomography (Table 2). Particle size reduction of bran has no significant effect on the porosity and air cell diameter. Due to the high amount of starch (74–82%), porosity of extrudates was high, ranging between 86% and 90%. Average cell wall thickness (t) ranged between 0.14 and 0.19 mm. Particle size reduction influenced t with only IB hydration regimen at 30% bran addition level. Average cell diameter ranged between 1.1 and 1.4 and 1.0–1.6 mm, whereas cell area values ranged between 1.0 and 1.5 and 0.9–2.0 mm^2 for coarse- and fine-particle sized bran extrudates, respectively. Both cell diameter and area varies with the expansion at the die exit. The bubble formation at the die exit occurs due to differences in in-barrel and ambient pressure and is mainly spontaneous which ultimately creates large structural variations in between replicates. Among microstructural parameters only cell wall thickness significantly increased by particle size reduction. Overall, particle size reduction, bran concentration and hydration regimen had no significant impact on the microstructural properties of the extrudate. This observation is in contrast with the results reported by Chanvrier et al. (2014). They showed that increasing amount of wheat bran (10–32%) and oat bran concentrate (10–26%) in whole grain wheat extrudates decreased porosity and average cell size when the total dietary fibre increased from 5 to 17%. In their studies bran was used in mixture with whole wheat, refined wheat and corn flours. Our current study indicates that there is a critical bran concentration below which particle size reduction of the bran does not influence micro-structural properties.

3.3. Textural properties

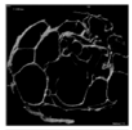
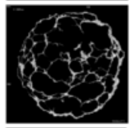
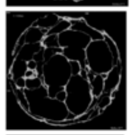
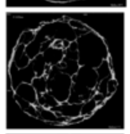
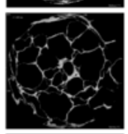
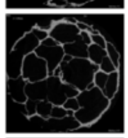
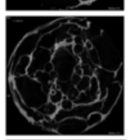
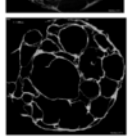
Structure and texture of snack foods are important for product quality and consumer acceptance. For extruded puffed snacks, expansion rate and crispiness are the most important quality parameters. Textural properties (e.g. hardness, crushing force, crispiness work and crispiness index) of the rye extrudates containing bran are shown in Fig. 2. Bran particle size had no significant effect on hardness (i.e., maximum force) but it showed positive correlation with the crushing force (i.e., average force) and crispiness work of extrudates. These results indicate that extrudates with coarse rye bran were less crispy (C_w: 2.9–3.3 N mm) than extrudates with fine bran (C_w: 1.7–2.6 N mm), except IB extrudates. Crispiness indices were significantly influenced by bran particle size. Addition of fine rye bran increased crispiness compared to the extrudates with coarse rye bran (Fig. 2). This suggests that a decrease in bran particle size allows higher bran addition without significant changes in product crispiness. Particle size was positively correlated with crushing force ($r = 0.83$, $P < 0.05$), crispiness work ($r = 0.85$, $P < 0.01$) and negatively with crispiness index ($r = -0.80$, $P < 0.05$). These correlations clearly indicate that the effect of particle size on the product texture was significant, and textural properties can be improved by reducing particle size of rye bran. However, extrudates processed with 30% fine-particle sized bran at IB hydration regimen were significantly crispier ($P < 0.05$) than the other extrusion recipes. This indicates that the combination of particle size reduction and selected hydration regimen i.e., in-barrel water feed could improve the textural properties of the fibre snacks. Our finding is in agreement with the result reported by Karkle et al. (2012), who showed that 28% fibre (apple po-

Table 3
Pearson's correlation matrix for macro-, microstructural and mechanical properties.

Variables	Correlations															
	Particle size	Bran conc.	Hydration regimen	Expansion rate	Specific length	Piece density	WAI	WSI	Porosity	Avg. Cell diameter	Avg. Cell wall thickness	Avg. Cell area	Hardness	Crushing force	Crispiness work	Crispiness index
Particle size (μm)	1	0.000	0.000	**−0.808***	**0.743***	0.638	−0.375	0.272	−0.114	−0.257	−0.706	−0,360	0.057	**0.825***	**0.845****	**−0.800***
Bran concentration (%)		1	0.000	−0.440	0.131	0.613	0.545	−0.649	−0.644	0.054	0.464	0.054	0.625	−0.185	−0.400	0.171
Hydration regimen (IB/PC)			1	0.067	0.121	−0.189	**0.708***	−0.640	−0.207	−0.553	−0.443	−0.529	−0.693	0.189	0.058	−0.187
Expansion rate (%)				1	**−0.833***	**−0.876****	0.078	0.120	0.333	0.082	0.248	0.171	−0.475	−0.452	−0.438	0.439
Specific length (mkg^{-1})					1	0.466	−0.030	−0.085	−0.152	−0.140	−0.432	−0.234	0.190	0.561	0.592	−0.515
Piece density (kgm^{-3})						1	−0.063	−0.150	−0.462	−0.063	−0.026	−0.122	0.585	0.248	0.184	−0.270
WAI							1	**−0.964****	−0.493	−0.228	0.212	−0.183	−0.184	−0.247	−0.455	0.207
WSI								1	0.499	0.147	−0.275	0.113	0.011	0.293	0.480	−0.252
Porosity (%)									1	0.628	0.018	0.629	−0.142	−0.258	−0.012	0.307
Avg. cell diameter (mm)										1	0.622	**0.993****	0.497	−0.564	−0.406	0.553
Avg. cell wall thickness (mm)											1	0.680	0.638	**−0.891****	**−0.894****	**0.866****
Cell area (mm^2)												1	0.475	−0.647	−0.498	0.636
Hardness (N)													1	−0.330	−0.324	0.356
Crushing force (N)														1	**0.952****	**−0.984****
Crispiness work (N mm)															1	**−0.934****
Crispiness index ($\times 10^{-4}$)																1

*Correlation is significant at the 0.05 level (2-tailed), **Correlation is significant at the 0.01 level (2-tailed).

Table 2
Microstructural parameters of extrudates containing coarse and fine particle-sized-rye bran.

Particle size	Sample	Representative image	Porosity (%)	D (mm)	t (mm)	Cell area (mm^2)
Coarse (440 μm)	IB 15		90 ± 1.1 [a]	1.4 ± 0.07 [ab]	0.14 ± 0.01 [a]	1.55 ± 0.15 [ab]
	IB 30		86 ± 1.1 [a]	1.1 ± 0.06 [ab]	0.16 ± 0.01 [ab]	1.02 ± 0.11 [ab]
	PC 15		89 ± 2.7 [a]	1.3 ± 0.22 [ab]	0.14 ± 0.01 [a]	1.36 ± 0.44 [ab]
	PC 30		87 ± 0.6 [a]	1.2 ± 0.07 [ab]	0.14 ± 0.00 [a]	1.12 ± 0.12 [ab]
Fine (28 μm)	IB 15		89 ± 1.5 [a]	1.5 ± 0.18 [ab]	0.17 ± 0.01 [bc]	1.73 ± 0.40 [ab]
	IB 30		89 ± 1.2 [a]	1.6 ± 0.11 [b]	0.19 ± 0.01 [c]	2.06 ± 0.29 [b]
	PC 15		88 ± 2.2 [a]	1.0 ± 0.36 [a]	0.15 ± 0.01 [ab]	0.86 ± 0.63 [a]
	PC 30		88 ± 2.7 [a]	1.3 ± 0.28 [ab]	0.16 ± 0.00 [abc]	1.41 ± 0.54 [ab]

D = Average cell diameter, t = Average cell wall thickness.
IB = in barrel–water feed, *PC* = preconditioning, 15 and 30% refers to the bran concentration.
Values followed by the **same letters** in the **same column** were **not** significantly different ($P < 0.05$).

mace) addition at 17.2% IB improved textural properties of corn-based extrudates by increasing crispiness.

Apparently, the effect of bran concentration on extrudate textural parameters is highly dependent on raw materials and processing conditions. In the current study, regardless of hydration regimen, increase in bran concentration from 15 to 30% increased hardness and decreased crispiness of the rye extrudates. Similar results were also reported by other researchers; e.g. 5–20% inclusion of wheat or oat bran significantly increased hardness and decreased crispiness of oat and wheat flour extrudates (Sibakov et al., 2014; Brennan et al., 2008). Robin et al. (2011a) found that extrusion of a mixture of wheat bran and wheat flour (to achieve fibre content of 24.4%) produced harder extrudates. Harder and less crispy extrudates were due to finer cellular structure and higher cell density of the bran-containing extrudates.

3.4. Starch hydrolysis index

Increasing total dietary fibre (TDF) content from 8.2% to 12.6% significantly ($P < 0.05$) reduced *in vitro* starch hydrolysis of the extrudates containing 30% fine bran. HI of the extrudates containing coarse bran (Table 4), however, was not significantly different within different bran concentration. Although the gradual decrease in the amount of starch was similar for coarse (80.9 → 74.1%) and fine bran (81.9 → 75.8%) extrudates due to the increased bran level, the decrease in HI was observed only for 30% fine bran extrudates. Also extrudates made from 100% fine rye bran with higher starch amount had significantly lower HI compared to 100% coarse rye bran extrudates (Table 4), which correspond to the results found with 30% fine bran extrudates. Identical HI value was obtained for both 30% and 100% fine bran extrudates even though the starch amount was 30.2% higher in 30% bran added extrudates. Therefore, it could be hypothesised that HI of fine bran extrudates was not only affected by the starch amount but also by microstructural architecture. However,

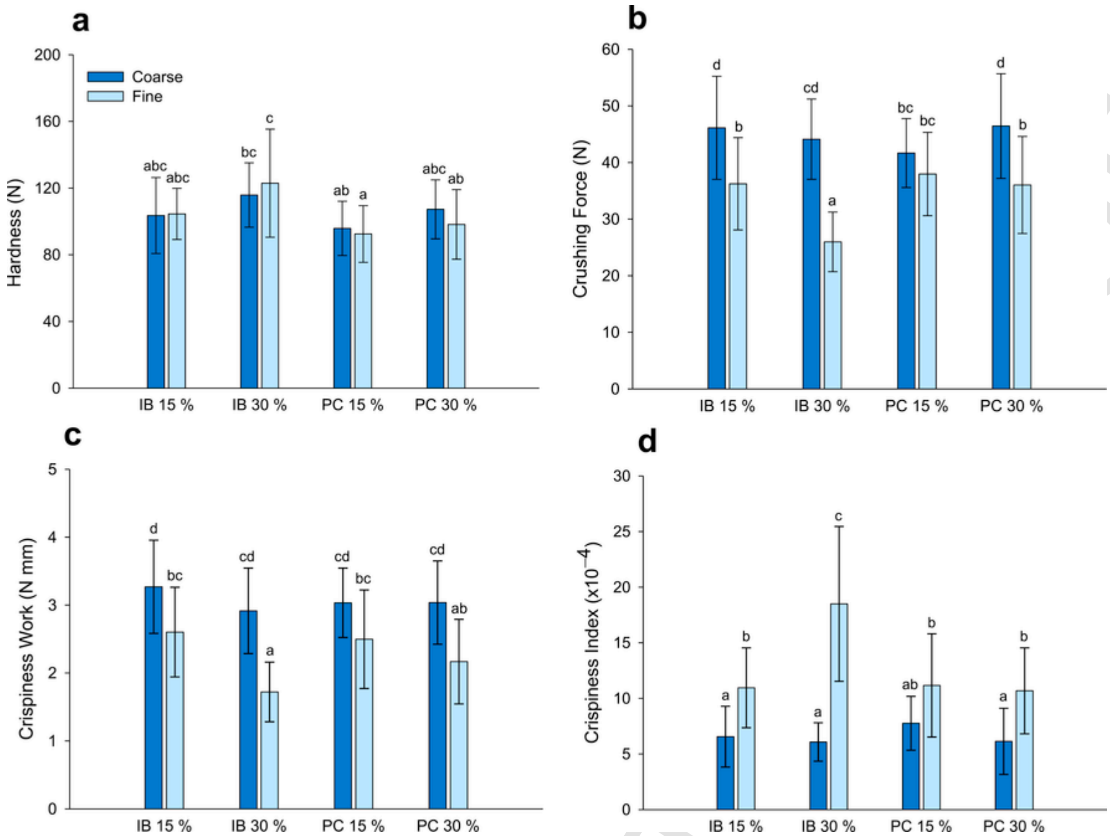


Fig. 2. a) Hardness, **b)** crushing force, **c)** crispiness work and **d)** crispiness index of the extrudates made with coarse-, and fine-particle-sized rye bran (15% and 30% inclusion) processed with 17% feed moisture in two different hydration regimens (*IB* in barrel–water feed, *PC* preconditioning) at 500 rpm and at 110 °C. Bars followed by the **same letters** in **each figure** were **not** significantly different ($P < 0.05$).

Table 4
Hydrolysis index (values are mean of three replicates) and starch content of extrudates containing coarse and fine particle-sized-rye bran.

Sample	HI	Starch (%, dry weight basis)
Coarse 15%	$70.3 \pm 1..9^{a}$	80.9 ± 0.4^{g}
Coarse 30%	66.9 ± 1.7^{a}	74.1 ± 0.3^{e}
Coarse 100%	75.4 ± 0.8^{b}	40.2 ± 0.1^{a}
Fine 15%	74.6 ± 1.5^{b}	81.9 ± 0.9^{g}
Fine 30%	69.0 ± 1.9^{a}	75.8 ± 0.4^{f}
Fine 100%	68.9 ± 1.9^{a}	45.6 ± 0.2^{b}
Wholegrain rye bread	80.8 ± 0.9^{c}	57.1 ± 0.6^{c}
White wheat bread	100.0 ± 0.0^{d}	70.0 ± 0.4^{d}

All extruded samples were processed with *IB* in barrel-water feed.
Values followed by the **same letters** in the **same column** were **not** significantly different ($P < 0.05$).

all extruded samples had lower HI than wholegrain rye bread regardless of starch amount.

High shear forces in the extruder barrel disrupt the structural integrity of starch granules and make them susceptible for enzymatic attack (Anguita et al., 2006; Altan et al., 2009). In earlier work, wheat bran, inulin and guar gum supplementation in extruded products at TDF levels of 5–15% reduced HI (Brennan et al., 2012); similar trend of reduced HI was obtained for grape and tomato pomace (Altan et al., 2009) as well as apple pomace (Karkle, 2011) supplemented extrudates with TDF levels of 15–21% and 1–23%, respectively. Adding soluble DF (such as inulin) and insoluble DF (such as wheat bran) gave slightly lower *in vitro* starch digestibility rate (Brennan et al., 2008).

In this study, 30% fine rye bran (TDF: 12.6%) extrudates had significantly ($P < 0.05$) thicker cell walls compared to 15% fine rye bran extrudates (Table 2). In our previous study, significantly ($P < 0.05$) higher cell wall thickness was observed for 100% fine bran extrudates (0.32 ± 0.04 mm) than 100% coarse bran extrudates (0.24 ± 0.01 mm) (Alam et al., 2014). Increased cell wall thickness might have reduced starch digestibility for 30% fine rye bran extrudates as large amount of starch granules could not come into contact with enzyme and remained intact. Anguita et al. (2006) found that particle size reduction (3000 → 800 μm) slightly increased starch hydrolysis rate of corn and wheat extrudates with crude fibre content of 2.4 and 3.3%, respectively. However, in the current study significant ($P < 0.05$) increase in the HI due to particle size reduction observed for only 15% bran addition level. Inverse relationship between starch digestibility and fibre addition level was pronounced only in case of fine rye bran extrudates. Brennan et al. (2008) showed that addition of either guar gum or wheat bran giving a TDF content of up to 15% still had high starch hydrolysis rate, which is in accordance with the results presented here.

3.5. Water absorption and solubility

Particle size reduction and increase in bran concentration increased water absorption (WAI) of extrudates, but the effect on water solubility (WSI) was opposite (Fig. 3). Fine rye bran extrudates resulted in higher WAI compared to coarse counterparts. Coarse rye bran contained larger pieces of aleurone layer than finely milled bran, which might reduce the rate of water penetration. Reduction of wheat bran particle size was also reported to increase WAI with increased

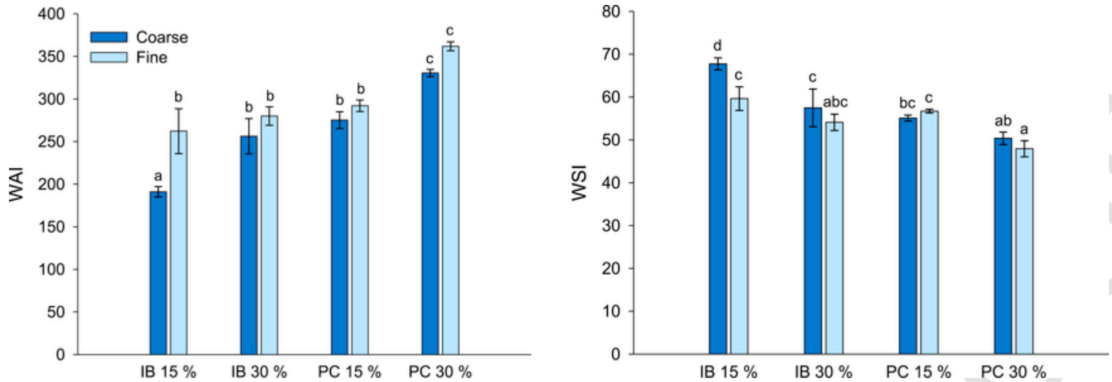


Fig. 3. Water absorption index (WAI) and water solubility index (WSI) of extrudates made with coarse-, and fine-particle-sized of rye bran (15% and 30% inclusion) processed with 17% feed moisture in two different hydration regimens (*IB* in barrel–water feed, *PC* preconditioning) at 500 rpm and at 110 °C. Bars followed by the **same letters** in **each figure** were **not** significantly different (P < 0.05).

ratio of soluble dietary fibre (SDF) to IDF (Zhu et al., 2010). In the current study, fine rye bran contained slightly higher amount of starch (44.8 vs. 38.4%) and SDF (5.5 vs. 4.9%) than coarse bran, which might have promoted higher WAI values. Comparatively lower amount of starch in coarse bran reduced the water swelling capacity and may thus have resulted in lower water absorption. Singh et al. (2007) pointed out that higher amount of starch in the feed material absorbs more water when gelatinized during extrusion, even at lower water (12–22%) level.

Increased bran addition increased WAI and decreased WSI. Similar results were also reported in other studies, where rice bran and wheat bran were added into the feed material (Robin et al., 2011b; Charunuch et al., 2014). Increases in bran concentration increased WAI due to the presence of higher amount of hydrophilic fibre particle. Higher level of bran addition might cause some structural modification in bran at high screw speed. High screw speed produces high specific mechanical energy inside the barrel and could probably induce a more open structure of fibre which allows more water to come in contact with hydrophilic groups. A negative correlation ($r = 0.96$, $P < 0.01$) was observed between WAI and WSI regardless of either bran addition level or particle size reduction. A negative correlation between WAI and WSI was also shown, regardless of wheat bran concentration (2.8%, 12.6% and 24.4%), in extrusion of wheat flour-bran mixture (Robin et al., 2011b). In preconditioned samples bran had more time to hydrate before extrusion leading to more complete gelatinization of starch and swelling of the fibres and thus to significant ($P < 0.05$) increase of WAI.

4. Conclusions

This study focused on starchy extrudates with added rye bran of two different particle sizes (coarse: 440 μm and fine: 28 μm) and showed that up to 30% of fine rye bran could be added without interfering with structural and textural properties. In barrel-water feeding improved the textural properties and reduced the *in vitro* hydrolysis index of 30% fine bran added extrudates, while preconditioning improved only the expansion rate. Increase in WAI, expansion and crispiness with decreased piece density and WSI was observed with particle size reduction, which however had no significant effect on hardness. Particle size reduction of bran had very minor effects on the porosity and cell diameter of the extrudates but cell wall thickness and cell area increased with reduced particle size. Hydrolysis index was slightly smaller at 30% addition of fine bran, but all the other extrudates had quite readily accessible starch. Extrudates supplemented with fine bran had better structural and textural properties than with coarse bran but there was minor influence on *in vitro* HI.

Uncited reference

Acknowledgements

This study was jointly funded by the Academy of Finland (Academy Professorship, Kaisa Poutanen - grant number 131460) and by the Raisio plc's Research Foundation (personal grant to Syed Ariful Alam, grant decisions of 2015). Dr. Kirsi Jouppila and Satu Kirjoranta from University of Helsinki are acknowledged for providing the extrusion facilities.

References

Alam, S.A., Järvinen, J., Kirjoranta, S., Jouppila, K., Poutanen, K., Sozer, N., 2014. Influence of particle size reduction on structural and mechanical properties of extruded rye bran. Food Bioprocess Technol. 7 (7), 2121–2133.

Altan, A., Maskan, M., 2011. Development of extruded foods by utilizing food industry by-products. In: Maskan, A., Altan, M. (Eds.), Advances in Food Extrusion Technology. CRC Press, Boca Raton, FL, pp. 121–160.

Altan, A., McCarthy, K.L., Maskan, M., 2009. Effect of extrusion cooking on functional properties and in vitro starch digestibility of barley-based extrudates from fruit and vegetable by-a products. J. Food Sci. 74 (2), E77–E86.

Anderson, R., Conway, H., Pfeifer, V., Griffin, E., 1969. Gelatinization of corn grits by roll and extrusion cooking. Cereal Sci. Today 14 (1), 4–12.

Anguita, M., Gasa, J., Martín-Orúe, S., Pérez, J., 2006. Study of the effect of technological processes on starch hydrolysis, non-starch polysaccharides solubilization and physicochemical properties of different ingredients using a two-step in vitro system. Anim. Feed Sci. Technol. 129 (1), 99–115.

Brennan, M.A., Derbyshire, E., Brennan, C.S., Tiwari, B.K., 2012. Impact of dietary fibre-enriched ready to eat extruded snacks on the postprandial glycaemic response of non-diabetic patients. Mol. Nutr. Food Res. 56, 834–837.

Brennan, M.A., Merts, I., Monro, J., Woolnough, J., Brennan, C.S., 2008. Impact of guar and wheat bran on the physical and nutritional quality of extruded breakfast cereals. Starch Stärke 60 (5), 248–256.

Chanvrier, H., Jakubczyk, E., Gondek, E., Gumy, J.-C., 2014. Insights into the texture of extruded cereals: structure and acoustic properties. Innov. Food Sci. Emerg. Technol. 24, 61–68.

Charunuch, C., Limsangouan, N., Prasert, W., Wongkrajang, K., 2014. Optimization of extrusion conditions for ready-to-eat breakfast cereal enhanced with defatted rice bran. Int. Food Res. J. 21 (2), 713–722.

Guan, J., Fang, Q., Hanna, M., 2004. Selected functional properties of extruded starch acetate and natural fibers foams. Cereal Chem. 81 (2), 199–206.

Hauner, H., Bechthold, A., Boeing, H., Brönstrup, A., Buyken, A., Leschik-Bonnet, E., Linseisen, J., Schulze, M., Strohm, D., Wolfram, G., 2012. Evidence-based guideline of the German Nutrition Society: carbohydrate intake and prevention of nutrition-related diseases. Ann. Nutr. Metab. 60 (1), 1–58.

Karkle, E.L., Keller, L., Dogan, H., Alavi, S., 2012. Matrix transformation in fibre-added extruded products: impact of different hydration regimen on texture, microstructure and digestibility. J. Food Eng. 108, 171–182.

Karkle, E.N.L., 2011. Carbohydrate Components of Pomace in Corn-based Extrudates: Interactions, Expansion Dynamics, and Structure-texture Relationships (Doctoral dissertation). Retrieved from K-State Electronic Theses, Dissertations, and Reports Kansas State University, Manhattan, Kansas, USA. http://hdl.handle.net/2097/12059.
Liu, S., Alavi, S., Abughoush, M., 2011. Extruded moringa leaf–oat flour snacks: physical, nutritional, and sensory properties. Int. J. Food Prop. 14 (4), 854–869.
Livesey, G., Taylor, R., Hulshof, T., Howlett, J., 2008. Glycemic response and health−a systematic review and meta-analysis: relations between dietary glycemic properties and health outcomes. Am. J. Clin. Nutr. 87 (1), 258S–268S.
Lue, S., Hsieh, F., Huff, H.E., 1991. Extrusion cooking of corn meal and sugar beet fiber: effects on expansion properties, starch gelatinization, and dietary fiber content. Cereal Chem. 68 (3), 227–234.
Mathew, J., Hoseney, R., Faubion, J., 1999. Effects of corn sample, mill type, and particle size on corn curl and pet food extrudates. Cereal Chem. 76 (5), 621–624.
Pai, D.A., Blake, O.A., Hamaker, B.R., Campanella, O.H., 2009. Importance of extensional rheological properties on fiber-enriched corn extrudates. J. Cereal Sci. 50, 227–234.
Robin, F., Dubois, C., Curti, D., Schuchmann, H.P., Palzer, S., 2011a. Effect of wheat bran on the mechanical properties of extruded starchy foams. Food Res. Int. 44 (9), 2880–2888.
Robin, F., Schuchmann, H.P., Palzer, S., 2012. Dietary fiber in extruded cereals: limitations and opportunities. Trends Food Sci. Technol. 28 (1), 23–32.
Robin, F., Théoduloz, C., Gianfrancesco, A., Pineau, N., Schuchmann, H.P., Palzer, S., 2011b. Starch transformation in bran-enriched extruded wheat flour. Carbohydr. Polym. 85 (1), 65–74.
Santala, O., Kiran, A., Sozer, N., Poutanen, K., Nordlund, E., 2014. Enzymatic modification and particle size reduction of wheat bran improves the mechanical properties and structure of bran-enriched expanded extrudates. J. Cereal Sci. 60 (2), 448–456.
Sibakov, J., Kirjoranta, S., Alam, S.A., Kokkonen, H., Jurvelin, J., Jouppila, K., Poutanen, K., Sozer, N., 2014. Effects of oat bran on extrudates made of defatted oats. Food Bioprocess Technol. 8 (2), 445–458.
Singh, J., Kaur, L., Singh, H., 2013. In: Henry, J. (Ed.), Food Microstructure and Starch Digestion. Advances in Food and Nutrition Research. vol. 70. Elsevier, UK, pp. 137–179.
Singh, S., Gamlath, S., Wakeling, L., 2007. Nutritional aspects of food extrusion: a review. Int. J. Food Sci. Technol. 42 (8), 916–929.
Smith, C.E., Tucker, K.L., 2011. Health benefits of cereal fibre: a review of clinical trials. Nutr. Res. Rev. 24 (01), 118–131.
Sozer, N., Poutanen, K., 2013. Fibre in extruded food products. In: Delcour, J.A., Poutanen, K. (Eds.), Fibre-rich and Wholegrain Foods – Improving Quality. Woodland, Cambridge, UK, pp. 226–272.
Sozer, N., Cicerelli, L., Heiniö, R.-L., Poutanen, K., 2014. Effect of wheat bran addition on in vitro starch digestibility, physico-mechanical and sensory properties of biscuits. J. Cereal Sci. 60 (1), 105–113.
Zhu, K., Huang, S., Peng, W., Qian, H., Zhou, H., 2010. Effect of ultrafine grinding on hydration and antioxidant properties of wheat bran dietary fiber. Food Res. Int. 43 (4), 943–948.