CHARACTERISATION OF WHEAT–OAT FLOUR EXTRUDATE: PHYSICOCHEMICAL AND B-GLUCAN ATTRIBUTES

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The objective of this study was to evaluate the effect of wheat–oat flour ratio on the physical properties and β -glucan characteristics of extrudates. Results showed that increasing the wheat–oat flour ratio resulted in a decrease in the water solubility index ($r^2=0.8567$) and hardness ($r^2=0.9316$), whereas the expansion ratio ($r^2=0.9307$) and water absorption index ($r^2=0.9061$) increased. Wheat flour generally caused an increase in L values from 57.81 to 62.94 providing bright samples. Few cells were observed at high wheat–oat flour ratios under a scanning electron microscope, and a smooth surface was noted. Meanwhile, the total ($r^2=0.9867$) and soluble ($r^2=0.9848$) β -glucan contents were inversely proportional to the wheat–oat flour ratio. Extrudates with added wheat flour had a high molecular weight, but wheat flour had no significant ($P<0.05$) effect on the viscosity of β -glucan extracts. Conclusively, incorporation of wheat flour at a wheat–oat flour ratio of 2.33 provides ready-to-eat food based on whole oat flour, on account of improving the texture and providing sufficient β -glucan contents (0.806 g/100 g) without significantly affecting β -glucan viscosity.

Keywords: twin-screw extrusion, whole oat flour, wheat flour, β -glucan

Extrusion cooking is a modern processing technology that combines mixing, heating, sterilising, and puffing functions to manufacture food (ŠÁRKA et al., 2016). During extrusion cooking, the characteristics of raw materials, such as structure, crystallinity, and thermal properties undergo physical and chemical transformations (OBUCHOWSKI et al., 2015). Furthermore, extrusion is a potential method of industrialising healthy ready-to-eat cereal food, because it allows products to achieve well-accepted quality (WANI & KUMAR, 2016) and improved antioxidant activity (SHARMA et al., 2012).

Among whole grains, oat has well-recognised health benefits. The Food and Drug Administration confirmed that soluble fibres (β -glucan) from oats can reduce low-density blood cholesterol and prevent coronary heart disease (FDA, 1997), which are correlated with the content, viscosity, and molecular weight of solubilised β -glucans in the gastrointestinal tract. The European Food Safety Authority also reported that oat β -glucan (3 g/day) is capable of actively reducing blood cholesterol (EU 1160/2011). Moreover, the functional properties of β -glucan such as water solubility and viscosity have made it possible to utilise oat in new

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food applications (SHARMA & GUJRAL, 2013). Since then, considerable interest has been devoted to oats for producing health-promoting food products.

However, the utilisation of whole oat flours for extrusion cooking has elicited minimal attention because of poor expansion and hard texture (MOISIO et al., 2015). Moreover, oat flour lacks gluten, which is present in wheat flour in higher amounts and important to food processing. It is commonly accepted that the gluten and their structure during processing determine the final organoleptic qualities of products. Logically, extrusion cooking of whole oat flour in combination with wheat flour should elicit more interest.

The objective of this study was to investigate the effect of wheat-oat flour ratio on the physical properties and β -glucan characteristics of whole oat flour extrudates and to determine the optimum wheat-oat flour ratio to obtain oat-based extruded products that can substantiate the health claims for oat β -glucan products. The graphical abstract of study can be seen in Figure 1.

Fig. 1. Graphical abstract of the study on wheat-oat flour extrudates

1. Materials and methods

1.1. Materials and sample preparation

Whole oat flour (with starch, protein, lipid, and β -glucan contents of 37.64, 15.58, 10.32%, and 3.16%, respectively) was supplied by the Academy of Agricultural Sciences of Baicheng (Jilin, China). Wheat flour (with starch, protein, and lipid contents of 54.37, 12.20, and 3.48%, respectively) was purchased from Wudeli Flour Co, Ltd., (Shandong, China). The wheat flour and whole oat flour were mixed thoroughly at ratios of 10:90, 30:70, 50:50, 70:30, and 90:10 (i.e., wheat-oat flour ratio=0.11, 0.43, 1.00, 2.33, and 9.00) and the moisture content was adjusted to 30% (wet weight).

1.2. Extrusion processing

Extrusion was performed in a laboratory twin-screw extruder (DS32-I, Jinan Saixin, China) (length/diameter ratio: 18.75, die diameter: 4.5 mm). On the basis of previous work (REGAND et al., 2011) and preliminary experiments, the extrusion parameters were set as follows: temperature profile: heating zone I, II, and III: 60, 120, and 150 °C; screw speed: 196 r.p.m.; and feed speed: 42 r.p.m. The extruded product was allowed to cool overnight at 25 °C prior to chemical and physical analyses.

1.3. Physical properties

1.3.1. Expansion ratio. The diameters of 50 mm long extrudates obtained randomly were measured at three different positions of samples by using a Vernier calliper. The expansion was calculated with Eq. (1) according to the procedure of SIBAKOV and co-workers (2015).

$$\text{Expansion ratio (\%)} = (D_e - D_d)/D_d \times 100 \quad (1)$$

where D_e is the average diameter of extrudates (mm) and D_d is the inner diameter of the dead nozzle (4.5 mm).

1.3.2. Water absorption index (WAI) and water solubility index (WSI). WAI and WSI were determined according to the recommendation of ANDERSSON and co-workers (2004). WAI and WSI were calculated using Eqs (2) and (3).

$$\text{WAI (\%)} = \text{weight of wet sediment/weight of dry sample} \times 100 \quad (2)$$

$$\text{WSI (\%)} = \text{weight of dry solids in supernatant/weight of dry sample} \times 100 \quad (3)$$

1.3.3. Colour. The colour of the samples was measured by a colorimeter (model WSC-S, Shanghai, China) using the Hunter Lab Colour Measuring System and D65 illuminant at 2° view angle.

1.3.4. Hardness. Hardness was measured with a texture analyser (Brookfield CT3, Middleboro, USA) via the method of AINSWORTH and co-workers (2007). Compression tests (two compression cycles) were performed in the mode “measure force in compression” with constant parameters (trigger value of 5 g, penetration depth of 3 mm, test speed of 0.4 mm s⁻¹, and re-speed of 0.5 mm s⁻¹).

1.3.5. Scanning electron microscopy. Samples were placed on a specimen holder and sputtered with gold particles (20 mA, 60 s). The surface morphology of the samples was recorded using a scanning electron microscope (JSM-6701F, Japan) at an acceleration voltage of 10 kV and a magnification of 4000.

1.4. β -Glucan characteristics

1.4.1. β -Glucan content. The β -glucan content of extrudates was determined by AOAC 995.16 using a mixed β -glucan linkage kit (Megazyme International Ltd., Ireland).

1.4.2. Extraction of soluble β -glucan. Soluble β -glucan was extracted by setting up an in vitro gastrointestinal digestion system (α -amylase, pepsin, and porcine pancreatin) according to a previous work (BEER et al., 1997). The supernatant after centrifugation was named soluble β -glucan extract.

1.4.3. Viscosity and molecular weight of soluble β -glucan extract. The viscosity of soluble β -glucan extract was determined using a rotational rheometer (TA Discovery Series, model HR-2, USA) according to TOSH and co-workers (2010). The molecular weight of soluble β -glucans was measured by high-performance size exclusion chromatography (HP-SEC) (1200 series, Agilent Technologies, China) combined with a differential refractometer (BI-DNC/GPC 620 nm, Brookhaven Instruments) according to LI and co-workers (2016).

1.5. Statistical analysis

The data were expressed as means $\pm$ standard deviation (SD). The statistically significant difference between values was evaluated through analysis of variance (ANOVA) using SPSS Statistics 20 (IBM, USA). The Pearson coefficient was applied for data correlation analysis.

2. Results and discussion

2.1. Expansion ratio and hardness

In general, a high expansion ratio and low hardness value improve product quality and taste (LI et al., 2017). The increasing expansion ratio ($r^2=0.9307$) (Fig. 2A) in this work could be due to the higher starch content in wheat flour (lower in protein and fibre) compared with whole oat flour. Meanwhile, fibres were able to reduce the expansion ratio by binding the water in the matrix. A similar result was obtained for extruded corn grit by WANG and RYU (2013), who reported that corn grit with a low corn fibre content had a high expansion index.

The hardness of the extrudate negatively correlated ($r^2=0.9316$) with the wheat flour mixture ratio (Fig. 2B). Swollen starch granules and water evaporation lead to a loose structure and reduced hardness. Furthermore, reduced protein led to a low resistance to shear and decreased hardness. AINSWORTH and co-workers (2007) reported that fibre could also increase the hardness by reducing the cell size and causing the rupture of gas cells. Meanwhile, a high expansion ratio indicated a high degree of gelatinisation of starch and a loose structure. Thus, hardness in this study was negatively correlated with expansion ratio ($P<0.05$) (Table 2) (JOZINOVIĆ et al., 2016).

Fig. 2. Effect of wheat-oat flour ratio on expansion ratio and hardness of whole oat flour extrudates. A) Expansion ratio. B) Hardness. Error bars indicate standard deviation. The thick black line indicates pure wheat flour, the thick grey line indicates pure oat flour.

2.2. WAI and WSI

The increase in the WAI ($r^2=0.9061$) implies the presence of large starch fragments in the final product, and the decreased WSI ($r^2=0.8567$) causes the reduction of dextrinised starch molecules (Fig. 3). The increase in WAI might be related to the increase in the expansion ratio ($r=0.9650$) (Table 2), which made the hydrophilic spots exposed (LI et al., 2017).

Moreover, low protein content also reduced the value of WSI. SETH and RAJAMANICKAM (2012) reported that protein contents in sorghum and soy blends increased the water solubility of extrudates. It is seen in Table 2 that higher total β -glucan and soluble β -glucan content lead to higher WSI ($r=0.9533$ and $r=0.9644$, respectively). A similar result was obtained by SHARMA and GUJRAL (2014), who reported that glucans from the barley flour, being water soluble fibres, come into the supernatant increasing the WSI.

Fig. 3. Effect of wheat-oat flour ratio on WAI and WSI of extrudates. A) WAI. B) WSI. The thick black line indicates pure wheat flour, the thick grey line indicates pure oat flour. Error bars indicate standard deviation.

2.3. Scanning electron microscopy and colour of oat extrudates

A smooth and melted surface was observed with increasing wheat flour mixture ratio (Fig. 4). The high fibre level decreased the expansion of the product, resulting a structure that contained many small cells. As shown in Table 1, no obvious functional relationship was observed between the colour value and wheat-oat flour ratio. AINSWORTH and co-workers (2007) indicated that these parameters are unsuitable for monitoring the colour of extruded snacks made from chickpea flour, maize flour, and oat flour.

Table 1. Colour values in L a b scale of oat extrudates with different ratio of wheat flour

Sample	L	a	b	ΔE
Pure oat flour	60.93 $\pm$ 0.63 ^a	0.29 $\pm$ 0.02 ^a	13.53 $\pm$ 0.57 ^a	7.81 ^a
Wheat-oat 0.11	57.81 $\pm$ 0.39 ^b	0.14 $\pm$ 0.21 ^a	14.26 $\pm$ 0.22 ^{bd}	11.14 ^b
Wheat-oat 0.43	58.55 $\pm$ 1.66 ^b	-0.03 $\pm$ 0.15 ^a	14.87 $\pm$ 0.07 ^c	11.72 ^{bc}
Wheat-oat 1.00	58.13 $\pm$ 0.57 ^b	-1.22 $\pm$ 0.17 ^b	14.49 $\pm$ 0.16 ^{cd}	13.41 ^c
Wheat-oat 2.33	59.52 $\pm$ 0.50 ^{ab}	-1.88 $\pm$ 0.23 ^c	14.42 $\pm$ 0.17 ^{cd}	13.50 ^c
Wheat-oat 9.00	60.90 $\pm$ 0.31 ^a	-3.10 $\pm$ 0.17 ^d	13.71 $\pm$ 0.15 ^{ab}	12.26 ^{bc}
Pure wheat flour	62.94 $\pm$ 0.56 ^c	-4.34 $\pm$ 0.21 ^e	14.09 $\pm$ 0.19 ^{abd}	11.42 ^b

L : brightness; a : (+) redness, (-) greenness; b : (+) yellowness, (-) blueness; ΔE represents the total colour difference between the sample and the standard white plate. Different letters indicate significant differences ($P<0.05$)

Fig. 4. Scanning electron microscopy of extrudates containing different ratio of wheat flour (4,000 $\times$), (A): Pure oat flour; (B): wheat-oat 0.11; (C) wheat-oat 0.43; (D) wheat-oat 1.00; (E) wheat-oat 2.33; (F) wheat-oat 9.00; (g) pure wheat flour

2.4. β -Glucan characteristics of extrudates

Extraction rate (Fig. 5C), which was defined as soluble β -glucan content/total β -glucan content, increased ($r^2=0.8941$) with the wheat-oat flour ratio, but was not within the range of pure oat flour and pure wheat flour. In addition, the molecular weights of the β -glucan of all extruded samples were mainly in the range of 0–10³ Da (Fig. 5A). On the other hand, increasing the wheat-oat flour ratio decreased the viscosity of the β -glucan extract at low wheat flour levels, but increased the viscosity at high wheat flour levels (Fig. 5B). ANTILA and co-workers (2004) showed that decreased concentration and increased molecular weight gave rise to increased viscosity. However, no significant relationship (Table 2) among these three factors was found in our study. This result might be attributed to the undigested components, such as resistant starch and small particles, which had a significant effect on the apparent viscosity of the polysaccharide solution. Arabinoxylans of wheat and oats might also play a role in this phenomenon. It was reported that arabinoxylans that have the potential to form viscous solutions might interact with β -glucan, thus affecting its characteristics (IZYDORCZYK & MACGREGOR, 2000). Moreover, the viscosity contributing to blood cholesterol reduction was independent of β -glucan characteristics and highly influenced by physical properties (Table 2) such as WAI ($r=0.6730$). This demonstrated that several of the water-absorbing substances in the blends, such as gelatinised starch and proteins, affected the viscosity of β -glucan extract.

Given that expansion and hardness were linearly related to the ratio, the consideration of β -glucan characteristics was important for rating the optimum ratio. We found that when the wheat-oat flour ratio was 2.33, extractability (Fig. 6A) was higher than that of pure oat flour and pure wheat flour, and the viscosity (Fig. 6B) was the closest to that of pure oat flour. To validate the health claims of blood cholesterol reduction and coronary heart disease prevention of oat β -glucan products, food must contain 0.75 g of β -glucan per serving (FDA, 1997), and 3 g daily consumption of β -glucan is required. According to the diluted amount of β -glucan, when calculated with 100 g (about a pack of puffed food) per serving, an extrudate

with a ratio of 2.33 could be still considered as oat product for containing 0.806 g/100 g of β -glucan, and 1/3 requirement of β -glucan could be consumed through this extrudate.

Table 2. Correlation coefficients between whole oat flour extrudate properties

Characteristics	ER	Hardness	WAI	WSI	TGC	SGC	Extraction rate	Viscosity
ER	1.0000	-0.8645*	0.9650**	-0.9250**	-0.8862**	-0.8967**	0.4171	0.4627
Hardness		1.0000	-0.7358	0.9269**	0.9901**	0.9727**	-0.7087	-0.1038
WAI			1.0000	-0.8236*	-0.7688*	-0.7558*	0.2822	0.6730
WSI				1.0000	0.9533**	0.9644**	-0.6414	-0.1777
TGC					1.0000	0.9918**	-0.6695	-0.0865
SGC						1.0000	-0.6027	-0.0814
Extraction rate							1.0000	-0.1417
Viscosity								1.0000

ER: expansion ratio; WAI: water absorption index; WSI: water solubility index; TGC: total β -glucan content; SGC: soluble β -glucan content.

**Significant at $P < 0.01$; *Significant at $P < 0.05$

Fig. 5. Effect of wheat-oat flour ratio on β -glucan content and extraction rate. A) Total β -glucan content. B) Soluble β -glucan content. C) Extraction rate. The thick black line indicates pure wheat flour, the thick grey line indicates pure oat flour. Error bars indicate standard deviation.

Fig. 6. β-Glucan characteristics of extrudates: A) Molecular weight distribution of β-glucan extracts. Black bars indicate $M_w > 10^5$ Da, white bars indicate 10^3 – 10^5 Da, and grey bars indicate 0 – 10^3 Da. B) viscosity of β-glucan extract. Error bars indicate standard deviation. Different letters indicate significant differences ($P < 0.05$).

3. Conclusions

This study found that wheat-oat flour ratio of 2.33 could be the optimum ratio to manufacture healthy extruded products with good quality, which could still bear health claims of oat β-glucan (0.806 g/100 g) products and supply 1/3 of the β-glucan required. Successful utilisation of wheat flour in whole oat flour extruded products will provide a new direction in food research and development.

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References

- AINSWORTH, P., İBANOĞLU, Ş., PLUNKETT, A., İBANOĞLU, 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.
- ANDERSSON, A.A., ARMÓ, E., GRANGEON, E., FREDRIKSSON, H., ANDERSSON, R. & ÅMAN, P. (2004): Molecular weight and structure units of (1→3, 1→4)-β-glucans in dough and bread made from hull-less barley milling fractions. *J. Cereal Sci.*, 40, 195–204.
- ANTTILA, H., SONTAG-STROHM, T. & SALOVAARA, H. (2004): Viscosity of beta-glucan in oat products. *Agr. Food Sci.*, 13, 80–87.
- 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.
- EU (2011): *The authorisation and refusal of authorisation of certain health claims made on foods and referring to the reduction of disease risk*. Commission regulation, (EU) No 1160/2011.
- FDA (1997): Final rule for food labelling: health claims: oat and coronary heart disease. *Federal Regulations*, 62, 3584–3681.
- IZYDORCZYK, M.S. & MACGREGOR, A.W. (2000): Evidence of intermolecular interactions of β-glucans and arabinoxylans. *Carbohydr. Polym.*, 41, 417–420.
- JOZINOVIĆ, A., ŠUBARIĆ, D., AČKAR, Đ., BABIĆ, J. & MILIČEVIĆ, B. (2016): Influence of spelt flour addition on properties of extruded products based on corn grits. *J. Food Eng.*, 172, 31–37.
- LI, C., KOWALSKI, R.J., LI, L. & GANJYAL, G.M. (2017): Extrusion expansion characteristics of samples of select varieties of whole yellow and green dry pea flours. *Cereal Chem.*, 94, 385–391.

- LI, Q., LIU, R., WU, T., WANG, M. & ZHANG, M. (2016): Soluble dietary fiber fractions in wheat bran and their interactions with wheat gluten have impacts on dough properties. *J. Agr. Food Chem.*, *64*, 8735–8744.
- MOISIO, T., FORSSELL, P., PARTANEN, R., DAMERAU, A. & HILL, S.E. (2015): Reorganisation of starch, proteins and lipids in extrusion of oats. *J. Cereal Sci.*, *64*, 48–55.
- OBUCHOWSKI, W., MAKOWSKA, A., MILDNER SZKUDLARZ, S., SZWENGIEL, A., MAJCHER, M. & REMISZEWSKI, M. (2015): Effect of triticale grain characteristics, scouring, and extrusion conditions on physico-chemical properties, antioxidant activity, and volatile compounds of flat bread. *Acta Alimentaria*, *44*, 511–519.
- REGAND, A., CHOWDHURY, Z., TOSH, S.M., WOLEVER, T.M.S. & WOOD, P. (2011): The molecular weight, solubility and viscosity of oat beta-glucan affect human glycemic response by modifying starch digestibility. *Food Chem.*, *129*, 297–304.
- SETH, D. & RAJAMANICKAM, G. (2012): Development of extruded snacks using soy, sorghum, millet and rice blend—a response surface methodology approach. *Int. J. Food Sci. Tech.*, *47*, 1526–1531.
- SHARMA, P., GUJRAL, H.S. & SINGH, B. (2012): Antioxidant activity of barley as affected by extrusion cooking. *Food Chem.*, *131*, 1406–1413.
- SHARMA, P. & GUJRAL, H.S. (2013): Extrusion of hulled barley affecting β -glucan and properties of extrudates. *Food Bioprocess Tech.*, *6*, 1374–1389.
- SHARMA, P. & GUJRAL, H.S. (2014): Anti-staling effects of β -glucan and barley flour in wheat flour chapatti. *Food Chem.*, *145*, 102–108.
- SIBAKOV, J.K., KIRJORANTA, J.S., ALAM, A., KOKKONEN, H., JURVELIN, J.S., ... & SOZER, N. (2015): Effect of oat bran fractions on extrudates made of defatted oats. *Food Bioprocess Tech.*, *8*, 445–458.
- ŠÁRKA, E., SMRČKOVÁ, P., KOLÁČEK, J., SAĞLAMTAŞ, M., CHENAALDAO, D. & POUR, V. (2016): Extrusion of corn grits with native or modified starch addition-influence on starch digestibility fractions, shear stress-at-break, and expansion ratio. *Acta Alimentaria*, *45*, 286–294.
- TOSH, S.M., BRUMMER, Y. & MILLER, S.S. (2010): Processing affects the physicochemical properties of β -glucan in oat bran cereal. *J. Agr. Food Chem.*, *58*, 7723–7730.
- WANG, Y.-Y. & RYU, G.-H. (2013): Physical properties of extruded corn grits with corn fibre by CO₂ injection extrusion. *J. Food Eng.*, *116*, 14–20.
- WANI, S. & KUMAR, P. (2016): Effect of incorporation levels of oat and green pea flour on the properties of an extruded product and their optimisation. *Acta Alimentaria*, *45*, 28–35.