Influence of the extrusion parameters on the physical properties of chickpea and barley extrudates

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Abstract In this research, the effects of extrusion processing [exit-die temperature (120–150°C), moisture content (20–24% wet basis), and screw speed (260–340 rpm)] on the specific mechanical energy and physical properties (expansion ratio, bulk density, and hardness) of desi chickpea and hull-less barley extrudates were estimated using response surface methodology. Exit-die temperature and feed moisture content, as well as the interaction between them were the factors that affected the product responses the most. Significant correlation was found between the hardness and bulk density (positive), hardness and expansion ratio (negative), and bulk density and expansion ratio (negative) for both chickpea and barley extrudates. Desirable characteristics (high expansion, low bulk density, and hardness) for chickpea were obtained at high exit-die temperature, relatively high moisture, and high screw speed. As for the barley extrudates, high exit-die temperature, low moisture, and moderate to high screw speed were identified as optimal.

Keywords: extrusion, chickpea, barley, flour, extrudate

Introduction

In the past, the food production industry was focused on cost reduction rather than improving the nutritive characteristics of products; however, now due to consumer awareness and demand, the challenge for the food industry is to supply nutritious and well-balanced food products, adapted to the market segmentation, using alternative technologies and ingredients (1). Extrusion cooking is a relatively new technique used to produce many different types of food products, including pasta, ready to eat breakfast cereals, baby foods, snacks, instant soups, biscuits, and many more, as it improves digestibility and nutrient bioavailability (2). Extrusion is a short time process in which food (feed) material is cooked by means of temperature, moisture, mechanical shear, and pressure, as it is forced through a die (3). As the material exits the die, the release of pressure causes it to puff in different shapes, based on the die geometry. The reactions that occur during extrusion cooking are dependent on a number of variables, being related both to the machine parameters and raw materials used (4).

In general, high expansion ratio, low bulk density, and a firm texture are desirable end product characteristics; these characteristics are governed by the properties of the raw materials and the extrusion process variables such as feed rate and moisture content, die diameter and shape, temperature, screw profile, and speed (3).

Barley is a valuable crop from a dietary point of view due to its high content of β -glucan. β -Glucan can help in lowering blood cholesterol levels and controlling blood sugar, as it binds cholesterol and bile acids, thus facilitating their elimination from the body (5). Although cereal grains are widely used and preferred in the production of extruded foods, due to their good expansion, they tend to be low in protein and other nutrients (6). Pulses, including chickpeas and beans, are not only an excellent source of protein, but also of complex carbohydrates, vitamins, and minerals (7). Chickpeas (*Cicer arietinum* L.) have one of the highest nutritional compositions amongst all edible pulses, as they are rich in protein (24.4%), dietary fiber (9.0%), and complex carbohydrates (60.0%) (6). In comparison to wheat flour, chickpea flour contains higher amounts of both macro- (potassium, calcium, and magnesium) and micronutrients (copper, iron, and zinc) (8). The average lipid content in chickpeas varies from 5.3 to 7.3% (9) and is characterized by high levels of linoleic acid (54.7–56.2% of oil), oleic acid (21.6–22.2% of oil), and linolenic acid (0.5–0.9% of oil) (8). With respect to chickpea's proteins, globulins and albumins are the major fractions, but small amounts of glutelins and prolamins can also be found (8). Due to their high lysine content, pulse flours can be used in different blend ratios to complement the amino acid profile of cereals, which are low in lysine. However, it is important to note that lysine availability has the potential to decrease with extrusion cooking due to the

Maillard reaction (10).

The main objective of this study was to investigate how the effects of extrusion processing variables, such as exit-die temperature, moisture content, and screw speed, on the specific mechanical energy (SME) and physical properties (expansion ratio, bulk density, and hardness) compare between desi chickpea and hull-less barley extrudates. Response surface methodology was used to study the effects as second-order polynomial regression models were used to fit the experimental data.

Materials and Methods

Materials Chickpea flour (Chana Flour Lot# DSP B14409) was purchased from Diefenbaker Seed Processors Ltd. (Elbow, SK, Canada) and pearled barley flour (Lot# 22515) was kindly donated by InfraReady Products (1998) Ltd. (Saskatoon, SK, Canada). Moisture and ash contents were determined according to AOCS Official Methods Ba 2a-38 and Bc 5-49, respectively. Protein content (%N×6.5) of the flours was determined by AOCS Ba 4e-93. Oil content was determined by the Swedish tube method (11). Resistant starch content was determined using Megazyme Resistant Starch Assay Kit (Megazyme International Ireland Ltd., Wicklow, Ireland) according to AOAC Method 2002.02. Starch content was determined according to AOAC Method 996.11. The chickpea flour and barley flour composition was as follows (on a wet basis): 10.20 and 9.10% moisture, 2.88 and 0.77% ash, 25.00 and 8.90% protein, 5.31 and 0.95% oil, 38.4 and 66.7% starch, 0.75 and 0.08% resistant starch, respectively.

Extrusion All extrusion experiments were performed using a co-rotating twin-screw extruder Cletral EV-32 (32 mm screw diameter; Firminy, France) with a length:diameter ratio of 24:1 using a die diameter of 3 mm. The screw profile consists of the first 80% of the screw length being conveying elements and the remaining 20% being reverse and conveying elements. The extruder barrel comprised six temperature zones. The first three zones (1–3) were constant and set to 50, 80, and 100°C, respectively. The temperatures of zones 4–6 were all the same and changed according to the experimental design (in this study, referred to as exit-die temperature). The last 3 zones were held at the same temperature to ensure the extruding mass was at the desired temperature in the working section of the screw (where the reverse elements were). The moisture content of each flour was determined prior to extrusion and then the total moisture of the extruding mass was adjusted by adding water into the extruder according to the experimental design. Formulations and extrusion conditions were allowed to stabilize for 7 min prior to taking the sample. The extruder was equipped with a volumetric feeder Cletral VF/40/25-2 and a Cletral 2-blade die face cutter. Based on preliminary trials, the extrudates were dried for 5 min at 105°C in a custom-built continuous conveyor dryer (Chromalox

Tunnel Dryer).

Experimental design and statistical analysis Rotatable central composite design (12), arranged in three blocks and randomized, was employed to estimate the effects of the extrusion processing variables on SME and physical properties of the extrudates. Additional center points were added (one per block) to provide a better measure of the inherent variability. The independent variables were the exit-die temperature (120–150°C), the moisture content (20–24% wet basis), and the screw speed (260–340 rpm). The feed rate was kept constant at 14 kg per h for all experiments as determined in preliminary extrusion trials. Second-order polynomial regression models were used to fit the experimental data (Eq. 1).

$$y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2 \quad (\text{Eq. 1})$$

where y is the response data, x_1 – x_3 are the experimental factors, b_0 the constant, b_1 – b_3 the linear coefficients, b_{11} , b_{22} , b_{33} the quadratic coefficients, and b_{12} , b_{13} , b_{23} the interaction coefficients. Statistica 10 (StatSoft, Inc., Tulsa, OK, USA) was used to design, estimate effects, and obtain the response surfaces.

Process and product responses

SME: The values of SME shown on the extruder control panel were recorded once a steady state was reached.

Expansion ratio (ER): ER was determined as the ratio between the diameter of the extrudates (measured with a digital caliper) and the diameter of the extruder die orifice ($\varnothing$ 3 mm). The average of six measurements is reported.

Bulk density (BD): BD was determined by weighing the quantity of extrudates required to fill a 500-mL container and reported in g/L (13). The extrudates were randomly added to the container and the container was shaken several times during filling. When the extrudates were more bulky (the barley extrudates, for example), a 1 L container was used instead. The average of two measurements for each processing condition is reported.

Hardness: Hardness was determined by measuring the maximum force required to break the extrudates. A thin blade shear compression cell (Model CS-2), which employs 13 parallel blades, each 1.5 mm in thickness, and a TMS-2000 Texture press with a 1,334 N load cell (Food Technology Corporation, Sterling, VA, USA) were used at a transducer speed of 0.33 cm/s. The average of at least three measurements is reported.

Results and Discussion

Effects of exit-die temperature, moisture content, and screw speed on SME During extrusion cooking, the raw materials are subjected to many order–disorder transitions, such as starch gelatinization and dextrinization, protein unfolding and denaturation, and also a

complex formation between lipids and amylose (14). The extent of these molecular transformations are strongly related to the mechanical energy input (15). The SME input during extrusion of chickpea flour was significantly ($p<0.01$) affected by the exit-die temperature and moisture content (Table 1). The linear effect of screw speed was not significant, but the quadratic effect and the interactions with exit-die temperature and moisture content were significant ($p<0.05$). Similar trends were observed for barley flour (Table 1). The exit-die temperature for chickpea flour influenced the SME the most; as for the barley flour, it was the moisture content. The response (fitted) surfaces (Fig. 1) showed that at low exit-die temperatures, an increase in the moisture content of chickpea flour would generate lower SME values, whereas for the barley flour, the SME input did not change with higher moisture content. Following the fitted surfaces, increasing the exit-die temperature and moisture content would give lower SME values for both flours. Regression coefficients and models fit (p -values) are presented in Table 2.

It is known that the interaction between water and temperature can significantly influence the conversion of starch (14). In an excess water environment, all the crystallites in starch will be pulled apart by swelling and complete starch gelatinization will occur. When water is limited, which is the condition during extrusion, the crystalline regions will melt at rather high temperatures. In this order of thoughts, water acts as a lubricant and softens the dough, therefore decreasing viscosity and SME. With an increase in the temperature of the dough, gelatinization and melting of the starch occur, and due to shear, these already gelatinized and melted starch granules are further mechanically broken down into smaller fragments, thus decreasing the viscosity of the melt. The extent of starch fragmentation is shown to be related to both mechanical and thermal energy and is reported to be in the form of limited debranching in amylopectin and random chain splitting in amylose (14).

Effects of exit-die temperature, moisture content, and screw speed on expansion ratio and bulk density

Exit-die temperature and

moisture content significantly ($p<0.05$) affected the expansion ratio (ER) of chickpea extrudates (Table 2). The interaction term between exit-die temperature and moisture content was also significant ($p<0.05$). The values of ER were in the range from 1.9 to 4.1 (with standard deviations between 0.1 and 0.8). According to the fitted surface (Fig. 2A and 2B; the lack of fit was significant at $p<0.05$) at low moisture content, the effect of temperature was less pronounced whereas an increase of both moisture and temperature would give higher expansion of the extrudates. In other words, the interaction effect between temperature and moisture was the most important factor for the product expansion. As for the barley extrudates (Table 2 and Fig. 2B), moisture and screw speed were the factors influencing the expansion the most. The quadratic effect of exit-die temperature on ER was also significant ($p<0.05$). The values of ER ranged from 3.2 to 4.8 (with standard deviations between 0.2 and 0.5). Higher expansion values of barley extrudates were obtained at low moisture and high screw speed. These results are consistent with other studies. For example, Baik *et al.* (3) reported that extrudates from barley flours had the highest expansion at 17% moisture and that increasing the screw speed results in higher expansion.

Exit-die temperature and screw speed significantly affected the bulk density of chickpea extrudates, as only the linear effects were significant ($p<0.05$) (Table 1). The values ranged from 103.3 to 467.7 g/L (with standard deviations between 0.3 and 28.3). Products with low bulk density were obtained at a high temperature and medium to high screw speed (Fig. 3A). As for the barley extrudates, bulk density was significantly ($p<0.05$) affected by all the factors, including all the three interaction terms (Table 1), with moisture content being the most important. The values were in the range from 44.8 to 147.4 g/L (with standard deviations between 0 and 2.3). According to the model obtained (Fig. 3B–3D; the lack of fit was significant at $p<0.05$), low moisture with relatively high temperature and moderate to high screw speed would give a product with low bulk density. For both, chickpea and barley extrudates, the interaction effect between exit-die temperature and moisture content on bulk density was highly significant ($p<0.01$).

Table 1. Effects of the extrusion processing variables on the specific mechanical energy (SME), expansion ratio (ER), bulk density (BD) and hardness of chickpea and barley extrudates

	Chickpea ¹⁾				Barley			
	SME, Wh/kg	ER, -	BD, g/L	Hardness, N	SME, Wh/kg	ER, -	BD, g/L	Hardness, N
(1) Exit-die temperature, °C (L) ²⁾	***	***	***	*	***	NS	***	***
Exit-die temperature, °C (Q)	NS	NS	NS	NS	NS	**	NS	NS
(2) Moisture, % (L)	***	***	NS	NS	***	***	***	***
Moisture, % (Q)	**	NS	NS	NS	NS	*	***	*
(3) Screw speed, rpm (L)	*	*	**	NS	NS	**	***	***
Screw speed, rpm (Q)	***	**	NS	NS	NS	**	**	**
1L by 2L	NS	***	***	NS	*	NS	***	NS
1L by 3L	***	NS	NS	NS	**	NS	**	**
2L by 3L	**	*	NS	NS	NS	*	**	*

¹⁾NS, not significant; * significant at $p<0.1$ (marginally significant); ** significant at $p<0.05$; *** significant at $p<0.01$

²⁾L, linear fit of the data; Q, quadratic fit of the data.

Table 2(A). Raw data for the specific mechanical energy (SME), expansion ratio (ER), bulk density (BD) and hardness of chickpea and barley extrudates used in the surface response curve

Exit die temp. (°C)	Moisture (%)	Screw speed (rpm)	Chickpeas				Barley			
			SME, Wh/kg	ER, -	BD, g/L	Hardness, N	SME, Wh/kg	ER, -	BD, g/L	Hardness, N
120	20.0	260	126.0	2.3	424.2	613.4	126.0	2.3	424.2	613.4
120	24.0	340	120.0	2.5	441.7	473.2	120.0	2.4	441.7	473.2
135	22.0	300	92.3	2.8	335.6	412.4	92.3	3.2	335.6	412.4
120	20.0	340	157.6	2.5	372.3	458.5	157.6	2.8	372.3	458.5
110	22.0	300	123.0	2.1	467.7	550.6	123.0	2.2	467.7	550.6
135	25.4	300	88.0	3.1	340.2	548.0	88.0	3.7	340.2	548.0
150	20.0	340	94.6	1.9	258.2	634.3	94.6	1.8	258.2	634.3
135	22.0	300	102.5	3.0	307.6	454.3	102.5	3.9	307.6	454.3
135	18.6	300	127.7	3.3	279.3	460.6	127.7	4.0	279.3	460.6
150	24.0	260	120.0	3.4	159.7	429.2	120.0	4.0	159.7	429.2
135	22.0	300	102.0	2.9	286.3	544.3	102.0	3.2	286.3	544.3
135	22.0	367	123.0	2.9	204.6	399.8	123.0	3.0	204.6	399.8
135	22.0	300	92.3	2.9	277.6	416.6	92.3	3.1	277.6	416.6
135	22.0	300	92.3	3.0	274.5	441.7	92.3	3.7	274.5	441.7
150	20.0	260	126.0	2.2	278.1	519.2	126.0	1.8	278.1	519.2
150	24.0	340	60.0	4.1	106.3	295.2	60.0	4.4	106.3	295.2
120	24.0	260	120.0	2.4	443.8	508.7	120.0	2.0	443.8	508.7
160	22.0	300	61.5	3.5	103.3	276.3	61.5	3.1	103.3	276.3
135	22.0	233	123.0	2.4	348.9	469.5	123.0	2.3	348.9	469.5
135	22.0	300	92.3	2.7	290.5	416.6	92.3	3.2	290.5	416.6

Table 2(B). Regression coefficients and models fit to the specific mechanical energy (SME), expansion ratio (ER), bulk density (BD) and hardness of chickpea and barley extrudates.

	Chickpea				Barley			
	SME, Wh/kg	ER, -	BD, g/L	Hardness, N	SME, Wh/kg	ER, -	BD, g/L	Hardness, N
Intercept	163.5056	43.4432	-1741.3047	797.2649	142.8202	-44.9195	93.1855	3505.2776
Block (1)	2.3981	0.0359	-1.5766	-25.9182	10.2751	0.0042	-0.6768	0.1993
Block (2)	-4.2044	0.1216	-14.6913	-23.8691	-6.4086	0.0919	0.0702	4.8403
(1) Exit-die temperature, °C (L)	5.8106	-0.2142	25.5128	20.8260	8.4604	0.2596	5.4463	-16.5052
Exit-die temperature, °C (Q)	0.0018	-0.0003	0.0050	-0.0132	0.0271	-0.0007	-0.0026	0.0204
(2) Moisture, % (L)	-44.2173	-2.8476	84.8988	-82.5011	-48.7298	1.6186	-26.7774	-90.5248
Moisture, % (Q)	1.4823	0.0145	2.4247	7.2838	1.6636	-0.0267	2.1215	1.3299
(3) Screw speed, rpm (L)	1.1872	0.0140	0.0397	-2.6567	1.4633	0.1073	-0.9597	-8.3754
Screw speed, rpm (Q)	0.0071	-0.0001	-0.0012	0.0028	0.0004	-0.0001	0.0013	0.0043
1L by 2L	0.0125	0.0140	-1.4973	-1.4133	-0.4544	-0.0014	-0.3210	0.1397
1L by 3L	-0.0256	0.0000	-0.0040	0.0357	-0.0240	-0.0002	0.0046	0.0236
2L by 3L	-0.0941	0.0015	0.0255	-0.2027	0.0755	-0.0016	-0.0321	0.1048
<i>p</i> -value for model lack of fit	0.43	0.04	0.16	0.24	0.11	0.78	0.03	0.14
<i>R</i> ²	0.97	0.82	0.95	0.67	0.84	0.98	0.99	0.95
Adj. <i>R</i> ²	0.93	0.56	0.89	0.22	0.62	0.95	0.97	0.86

Effects of exit-die temperature, moisture content, and screw speed on hardness In this experimental design, none of the factors significantly affected the hardness of chickpea extrudates; however, the exit-die temperature was marginally significant ($p < 0.1$). The hardness of the extrudates ranged between 276.3 and 634.3 N (with standard deviations between 6.3 and 74.4). Low values for hardness were obtained at high exit-die temperature, high moisture, and high screw speed. As for the barley extrudates, hardness was affected by all three factors, as the interaction between temperature and screw

speed was also significant ($p < 0.05$) (Table 1). The hardness of barley extrudates ranged between 184.2 and 311.9 N (with standard deviations between 3.6 and 25.2). Fitted surfaces showed that low moisture, high temperature, and moderate to high screw speed would give barley extrudates with lower hardness values (Fig. 4A-4C). The barley extrudates had superior quality characteristics in comparison to the chickpea extrudates. In general, materials low in protein (high in starch) tend to form low-density puffed-type products, whereas materials high in protein (low in starch) tend to

Fig. 1. Fitted surfaces profiles of specific mechanical energy as a response of exit-die temperature and moisture content for (A) chickpea flour and (B) barley flour.

Fig. 2. Fitted surfaces profiles of the expansion ratio for (A) chickpea extrudates as a response of exit-die temperature and moisture content and (B) barley extrudates as a response of screw speed and moisture content.

form denser texturized products (16). In the present study, the chickpea flour had a starch content of 38.4% (wb) and protein content of 25.0% (wb), whereas the values for the barley flour were 66.7 (wb) and 8.9% (wb) for starch and protein content, respectively. For expanded cereals, a starch concentration of 60–70% has been recommended; moreover, the expansion and starch concentration were shown to be proportional (13). Also, starches do not expand equally due to the difference in their structure; branched fractions were shown to influence the expansion (17). Proteins may have a positive or negative effect on the expansion due to their ability to

change water distribution within the matrix and depending on the type and concentration of protein (15). The higher fat content might also be responsible for the lower expansion and the inferior quality of the chickpea extrudates. Due to the lubricating effect of fat and by preventing the starch molecules from acute mechanical breakdown by the imposed shear forces, the degree of starch conversion decreases, which negatively affects the expansion (15).

Significant ($p < 0.05$) correlation was found between the hardness and bulk density (positive), hardness and expansion ratio (negative), and bulk density and expansion ratio (negative), for both chickpea

Fig. 3. Fitted surfaces profiles of bulk density for (A) chickpea extrudates as a response of exit-die temperature and screw speed; (B) barley extrudates as a response of exit-die temperature and screw speed; (C) barley extrudates as a response of exit-die temperature and moisture; and (D) barley extrudates as a response of screw speed and moisture.

and barley extrudates. These findings are consistent with other studies. Rayas-Duarte *et al.* (18) reported a negative relation between expansion index and breaking strength and a positive correlation between breaking strength and bulk density when comparing the extrudate quality of blends containing buckwheat flour. Specific mechanical energy was found to correlate with the expansion ratio. It was negative for chickpea extrudates ($r=0.57$, $p<0.05$) and positive for barley extrudates ($r=0.55$, $p<0.05$). Altan *et al.* (19) reported positive correlation between SME and the sectional expansion index (SEI) of barley extrudates, as affected by the screw configuration (medium and severe) and raw material (barley flour and barley grits). In this study, by employing a rotatable central composite design, the

effects of exit-die temperature, moisture content, and screw speed on the SME and physical properties (expansion ratio, bulk density, and hardness) of chickpea and barley extrudates were estimated. For the chickpea flour the exit-die temperature influenced the SME the most; whereas for the barley flour the moisture content influenced the SME the most. Increasing the exit-die temperature and moisture content generated lower SME values for both flours. Desirable characteristics (high expansion, low bulk density, and low hardness values) for chickpea were obtained at high exit-die temperature, relatively high moisture, and high screw speed. As for the barley extrudates, high exit-die temperature, low moisture, and moderate to high screw speed were identified as optimal.

Fig. 4. Fitted surfaces profiles of hardness for barley extrudates as a response of (A) exit-die temperature and moisture; (B) exit-die temperature and screw speed; and (C) screw speed and moisture.

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