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Extrusion cooking of barley flour and process parameter optimization by using response surface methodology

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Abstract

BACKGROUND: The nutritional profile of barley places it in a prime position for development of a new extruded–expanded snack food with health benefits. It was therefore the aim to investigate the effect of extrusion processing variables on system parameters (specific mechanical energy, die pressure and die melt temperature) and physical properties (expansion, bulk density, texture and color) of barley flour extrudates and to optimize processing conditions for production of extruded snack food from barley flour by response surface methodology.

RESULTS: Barley flour with 219.7 g kg^{-1} moisture content was extruded at different die temperatures (140–160 °C) and screw speeds (150–200 rpm) through a co-rotating twin-screw extruder. The system parameters as well as product responses were mainly dependent on temperature, whereas the screw speed imparted a lesser effect. Extrudates produced under extrusion conditions of 160 °C, 150 and 200 rpm and at 164 °C and 150 rpm had higher preference levels of appearance, taste, texture and overall acceptability than that of other selected extrudates for sensory analysis. The optimal conditions for minimum bulk density and desired textural characteristics and color of extrudates correspond to a temperature of 156 °C and screw speed of 166 rpm.

CONCLUSION: The results suggested that use of barley flour in extruded snack products offers a desirable variation in diet and can take advantage of the nutritional quality of barley.

Keywords: extrusion cooking; barley; RSM; optimization

INTRODUCTION

Barley is among the most ancient of the cereal crops. It is the fourth most important cereal in the world after wheat, rice and corn.[1] Barley is a new and different flavor alternative for today's consumers. The current interest in barley is the ability to promote good consumer health through its nutritional components such as fiber (especially β-glucan), antioxidants and B vitamins. Barley contains high levels of β-glucans, which are important contributors to dietary fiber and have significant blood cholesterol-lowering effects.[2,3] One mechanism by which they may exert their effects is through increasing intestinal viscosity and in this way reduce cholesterol and glucose absorption[4], which is beneficial in the management of diabetes.[5] The nutritional profile of barley places it in a prime position for development as a functional food with health benefits. It is an easily available and inexpensive crop, and barley flour products have the potential to appeal to health-conscious consumers of all ages as a functional food with health benefits, or simply as an alternative to existing products. There is a prime opportunity for increased commercialization of barley flour today due to increasing availability in the supply chain, additional research confirming the health benefits, consumer demand for healthy foods and the favorable reception of barley by consumers.

Considering the high nutritional quality of barley and the competitive nature of the market for functional foods, an extruded barley snack product has potential. Extrusion processing is one method by which an expanded snack food can be produced. Extrusion cooking has become a well-established industrial technology, with a number of foods and feed applications. In addition to the usual benefits of heat processing, extrusion offers the possibility of modifying the functional properties of food ingredients and/or of expanding them. Extrusion cooking as a continuous cooking, mixing and forming process is a versatile and very efficient technology in food processing.[6]

Response surface methodology (RSM) is an important tool in process and product improvement. RSM is a collection of experimental design and optimization techniques that enables the experimenter to determine the relationship between the response and the independent variables. RSM is typically used for mapping

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a response surface over a particular region of interest, optimizing the response, or for selecting operating conditions to achieve target specifications or customer requirements.[7] Extrusion processes can be optimized by the use of RSM.[8]

The objectives of this study were therefore to investigate the effect of the extrusion processing variables, namely extrusion die temperature and screw speed, on system parameters (specific mechanical energy (SME), die pressure and die melt temperature) and physical properties (expansion, bulk density, texture and color) of barley flour extrudates and to optimize processing conditions for production of extruded snack food from barley flour by RSM.

MATERIALS AND METHODS

Materials

Barley flour was obtained from Bob's Red Mill Natural Foods (Milwaukie, OR, USA). Table 1 shows the particle size distribution of barley flour. Barley flour was stored at 4 °C until use. Analyses of proximates, dietary fiber and starch from the barley were performed by Silliker, Inc. (Modesto, CA, USA). Analyses of moisture content, ash, protein (Kjeldahl, protein factor: 6.25) and starch (Ewers' starch) were performed according to approved methods described in AOAC.[9] The carbohydrate content was calculated by difference.

Sample preparation

The samples were conditioned to $219.7 \pm 4.8\,\mathrm{g\,kg^{-1}}$ (w.b.) moisture by spraying with a calculated amount of water and mixing continuously at medium speed in a mixer (model F-30T, Blakeslee, Chicago, IL, USA). The level of moisture content was chosen according to preliminary tests and to ensure smooth operation of the laboratory-scale extruder. Samples were placed in covered buckets and stored at 4 °C overnight. The feed material was then allowed 3 h to equilibrate at room temperature prior to extrusion. This preconditioning procedure was employed to ensure uniform mixing and hydration and to minimize variability in the state of the feed material. Moisture content of samples was determined using a halogen moisture analyzer (models HR83 and HR83P, Mettler-Toledo GmbH, Greifensee, Switzerland) at 105 °C.

Table 1. Particle size distribution of barley flour

Particle size (μm)	Distribution (g kg^{-1})
>420	121
250–420	429
177–250	389
149–177	55
125–149	4
125	2

Extrusion cooking

The extrusion was carried out on a laboratory-scale co-rotating twin-screw extruder (MPC/V-30 model, APV, Newcastle Under Lyme, UK), equipped with a computer control and data acquisition system and a System 9000 torque rheometer (Haake Buchler, Paramus, NJ, USA). The extruder had a barrel diameter of 30 mm and length–diameter ratio (L/D) of 13:1 and had a slit die (Haake Buchler) of 1.47 mm × 20 mm × 150 mm. The MPC/V-30 had a clamshell barrel consisting of three independent zones and transition section temperatures controlled by electrical heating and compressed air cooling. A computerized control and data acquisition system were used to control five set temperatures and rotor speed and to record five melt temperatures, pressure at the slit die and torque data. Data acquisition rate was every 6 s. The barrel zone temperatures were set constant at 30, 60 and 100 °C; the temperature of the transition section between the barrel and the die was set at 130 °C throughout the experiments. The die temperature was changed according to the experimental design. The actual extruder screw speed was 2.5 times the rotor speed. The screws were composed of screw elements and lope-shaped paddles which could be assembled on the hexagon-shaped shafts to give different screw configurations. The screw configuration used is shown in Fig. 1. The screw configuration used in the experiments consisted of three twin-lead feed screws (1.5D), two twin lead feed screws (1D), nine kneading elements oriented at 30° feed forward, one single-lead feed screw (1D) followed by nine kneading elements oriented at 30° feed forward and discharge screw (1D). Barley flour was fed into the extruder with a K-tron type T-20 twin-screw volumetric feeder (K-Tron Corp., Pitman, NJ, USA) at a rate of $2.09 \pm 0.05\,\mathrm{kg\,h^{-1}}$. Expanded extrudate was collected when the operation condition was at steady state, identified by torque values that

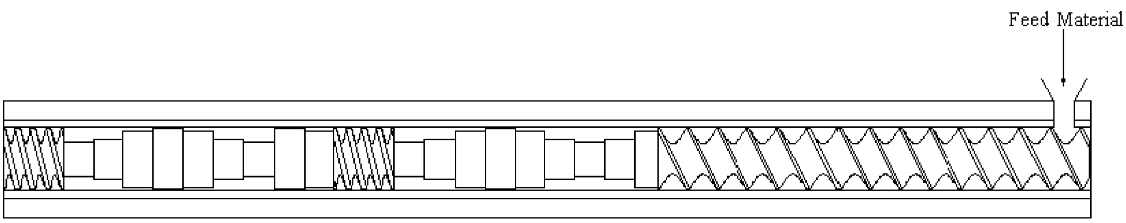

Figure 1. Schematic representation of screw configuration (three twin-lead feed screws (1.5D), two twin-lead feed screws (1D), nine kneading elements oriented at 30° feed forward, one single-lead feed screw (1D) followed by nine kneading elements oriented at 30° feed forward and discharge screw (1D)).

varied less than 5%. The samples were dried at 52 °C overnight in a forced-air drier (model # R-4, Commercial Dehydrator Systems, Inc., Eugene, OR, USA). The final dried samples contained a maximum of 47 g kg^{-1} (w.b.) moisture. Dried samples were stored in polyethylene bags at room temperature and used for further analysis.

Experimental design and data analysis

A five-level, two-variable, central composite design was used. The independent variables were die temperature (X_1) and screw speed (X_2). These variables were coded at levels of −1.414, −1, 0, +1 and +1.414. Actual values of variation levels and experimental design for the experiments are shown in Table 2. The range of variables was established based on literature data and preliminary trials. Dependent variables were specific mechanical energy (SME), die melt temperature, die pressure as system parameters and sectional expansion index (SEI), bulk density, texture and color as product responses. RSM was applied to experimental data using a commercial statistical package – Design-Expert version 6.0.6 (Statease Inc., Minneapolis, MN, USA) – for the generation of response surface plots. The same software was used for statistical analysis of experimental data. The results were analyzed by a multiple linear regression method which describes the effects of variables in first- and second-order polynomial models. Experimental data were fitted to the selected models and regression coefficients obtained. Statistical significance of the terms in the regression equation was examined by analysis of variance (ANOVA) for each response. A Pearson's correlation matrix on product responses and system parameters and also between sensory attributes and textural parameters were carried out using SPSS 11.0 (SPSS Inc., Chicago, IL, USA) in order to determine correlation coefficients between parameters. Duncan's multiple range test was performed for sensory data to determine differences between treatments by using SPSS.

Table 2. Experimental design for extrusion experiment with coded and actual variable levels

	Coded levels		Actual levels	
Run	X_1	X_2	Die temperature (°C)	Screw speed (rpm)
1	−1	−1	140	150
2	1	−1	160	150
3	−1	1	140	200
4	1	1	160	200
5	−1.414	0	136	175
6	1.414	0	164	175
7	0	−1.414	150	140
8	0	1.414	150	210
9	0	0	150	175
10	0	0	150	175
11	0	0	150	175
12	0	0	150	175
13	0	0	150	175

Moreover, numerical optimization was carried out for independent variables of extrusion cooking of barley flour. For this purpose, the desirability function of RSM was used. Desirability functions are one of the useful approaches to optimization of multiple responses. The desirability approach consists of the following steps: (1) Conduct experiments and fit response models (y_i) for all m responses. (2) Define individual desirability functions for each response (d_i). (3) Maximize the overall desirability with respect to the controllable factors.[10] The general approach is first to convert each response y_i into an individual desirability function d_i that varies over the range $0 \leq d_i \leq 1$ where, if response y_i is at its target value, then $d_i = 1$, and if it is outside an acceptable region, $d_i = 0$. The design variables were then chosen to maximize the overall desirability as

$$Do = (d_1 d_2, \ldots, d_m)^{1/m} \qquad (1)$$

where m is the number of responses and Do is the overall desirability. Design-Expert uses direct search methods to maximize the desirability function Do. Because the individual desirability functions are not differentiable, overall desirability is computed by Design-Expert for evaluation of optimal processing conditions.[7]

System parameters

SME, the net mechanical energy input (after no-load correction) divided by mass flow rate, provides a good characterization of the extrusion operations. SME input was calculated using following equation:[11]

$$\text{SME (W h kg}^{-1}\text{)} = \frac{\text{screw speed (rad s}^{-1}\text{)} \times \text{net torque (N m)}}{\text{mass flow rate (kg h}^{-1}\text{)}} \qquad (2)$$

SME was calculated from torque values recorded every 6 s for at least 12 min and averaged for each processing condition. Die pressure was measured using a Dynisco pressure transducer (PT-412, Dynisco, Franklin, MA, USA). Readings were recorded every 6 s for at least 12 min and average values were expressed as kPa. Die melt temperature was also measured by thermocouple and monitored for every 6 s by the computerized data acquisition system.

Product responses

Expansion

Extrudate expansion was determined as sectional expansion. A digital caliper was used to measure the width and thickness of extrudates. The average of 15 measurements of extrudate was used to calculate SEI. SEI was calculated by dividing the cross-section area

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of extrudate by the cross-section area of the slit die as given in Eqn (3):[12]

$$\mathrm{SEI} = \frac{S_e}{S_d} = \frac{W_e \times h_e}{W_d \times h_d} \quad (3)$$

where S_e and S_d are the cross-sectional areas of the extrudate and the die; W_e and h_e are the width and thickness of the extrudate and W_d and h_d are the width and thickness of the die respectively.

Bulk density

A volumetric displacement method by using glass beads with a diameter in the range of 1.00–1.18 mm as a displacement medium was used to determine bulk density of dried extrudates.[13] Bulk densities of the extrudates were calculated by using Eqn (4):

$$\rho_b = \frac{W_{ex}}{W_{gb}} \times \rho_{gb} \quad (4)$$

where ρ_b = bulk density using glass bead displacement method (g cm^{-3}), W_{ex} = extrudate mass (g), W_{gb} = mass of glass beads displaced (g) and ρ_{gb} = density of the glass beads (g cm^{-3}). The values were an average of four measurements.

Texture

The peak force as an indication of hardness was measured with a TA-XT2i texture analyzer (Texture Technologies Corp., Scarsdale, NY, USA). Hardness (N) was determined by measuring the maximum force required to break the extruded samples (~42 mm long) using a three-point bend test with a sharp-bladed probe (55 mm wide, 40 mm high, 9 mm thick). The slope (N mm^{-1}) and distance (mm) were measured from the force–distance curve and evaluated as crispness and brittleness respectively.[14,15] The test speed was 2 mm s^{-1} and the distance between two supports was 22 mm. A force–distance curve was recorded and analyzed using the Texture Exponent 32 software program (version 3.0). Eight measurements were performed on each sample and averaged.

Color

The extrudates were ground in a laboratory grinder (model DCG-12BC, Cuisinart, East Windsor, NJ, USA) and passed through a 60-mesh sieve prior to color analysis. Color values of the raw materials and ground extruded samples in terms of L (lightness), a (redness) and b (yellowness) were measured in a HunterLab LabScan XE (Hunter Associates Laboratory, Inc., Reston, VA, USA). The measuring head used was a 51 mm diameter viewing port and the system had diffuse illumination with 10° viewing geometry. The illuminant was D65. The colorimeter was calibrated against a standard white tile ($L = 91.43$, $a = -0.74$, $b = -0.25$). For each sample, four measurements were taken and averaged. The total color difference (ΔE) was calculated as follows:

$$\Delta E = \sqrt{(L - L_o)^2 + (b - b_o)^2 + (a - a_o)^2} \quad (5)$$

where the subscript 'o' indicates initial color values of the raw material.

Sensory analysis

Sensory analysis was performed for selected extrudates from six experiments out of 13 in terms of appearance, taste, off-odor, texture and overall acceptability. A semi-trained panel of 35 students and from faculty from the Food Engineering Department at the University of Gaziantep (Turkey) evaluated the extruded snacks for appearance (color and porosity), texture (hardness, crispness and brittleness) and overall acceptability on a 7-point hedonic scale (from 1 = extremely dislike to 7 = extremely like), while taste (bran flavor and bitterness) and off-odor were rated on a different 7-point scale (from 1 = none to 7 = very high). The samples of approximately 5 g were presented in white cups labeled with random letters. The extrudates were offered to panelists at the same moisture content. Evaluation was conducted in individual air-conditioned booths at room temperature (23 °C). The flavor attributes were evaluated under red lighting, while incandescent light was used for appearance and texture attributes. Panelists rinsed their mouths with water after tasting each sample. All sensory attributes were presented before sensory analysis. The sheet that contains definitions of sensory attributes was also placed in individual booths. Panelists evaluated hardness as the amount of force required to break the sample on first chew with molars. Crispness was measured as the degree to which breaking noise was heard. Brittleness was measured as capacity of a sample to break up into numerous pieces during the first bite. Porosity was visually evaluated as number of pores per unit area by panelists.

RESULTS AND DISCUSSION

The composition of barley (on dry basis) was 17, 857, 23 and 103 g kg^{-1} for ash, carbohydrates, fat and protein, respectively. The starch content was 684 g kg^{-1} dry matter.

Diagnostic checking of fitted model and surface plots for various responses

Specific mechanical energy

A multiple linear regression equation of second-order polynomial model was generated relating SME as system parameters to coded levels of variables. The regression model Eqn (6) allowed prediction of the effects of independent variables on SME:

$$\mathrm{SME} = 208.85 + 26.0X_2 - 14.88{X_1}^2 \quad (6)$$

An ANOVA was conducted to assess the significant effects of the independent variables on responses and which of the responses were significantly affected by the varying processing conditions. Regression analysis indicated that the fitted quadratic model had a coefficient of determination (R^2) of 0.9037 in the

Table 3. Analysis of variance of different models for the responses of barley extrudates

	Sum of squares								
Regression	SME	DP	SEI	BD	PF	*S*	Do	*L* value	Δ*E*
Model	10055.33*	3.435×10^6*	0.70*	0.83*	798.17*	201.53*	0.36*	4.70*	7.26*
Lack of fit	651.59 n.s.	1.158×10^6*	0.081 n.s.	0.013 n.s.	12.52*	4.03*	0.060*	3.73*	1.96 n.s.
Pure error	419.87	4.965×10^4	0.071	6.857×10^{-3}	0.12	0.27	6.306×10^{-3}	0.17	0.48
CV (%)	5.55	11.79	8.69	9.80	11.58	8.14	10.25	0.81	10.18
R^2	0.9037	0.7399	0.8210	0.9772	0.9844	0.9791	0.8462	0.5469	0.7489

* Significant at $P < 0.05$; n.s., not significant.

experimental data. Table 3 shows that the model for SME was significant ($P < 0.05$), whereas lack of fit was not significant ($P > 0.05$). SME was highly significant on the linear term of screw speed (X_2) ($P < 0.001$) and the quadratic term of temperature (X_1) ($P < 0.05$). The positive coefficient of the first-order term of screw speed (X_2) (Eqn 6) indicated that SME increased with increase of this variable, while the negative coefficient of the quadratic term of temperature (X_1) suggested that excessive increase of this variable resulted in decrease of SME.

The values for SME in extrusion cooking of barley flour varied from 158 to 248 W h kg^{-1}. Figure 2 shows the response surface graph of SME *versus* temperature and screw speed. SME increased with increase in screw speed. This was consistent with previous findings.[11,16,17] Baik *et al.*[17] reported that the increase in SME was due to the increase in shear rate when the screw speed was raised. Jin *et al.*[18] also reported that SME (specific energy) increased with increasing screw speed when the effect of screw speed was greater than that of dough mass viscosity. An increase in temperature beyond 150 °C caused a decrease in SME. This can be explained by a further increase in temperature causing a decrease in viscosity and hence a decrease in SME input.[11]

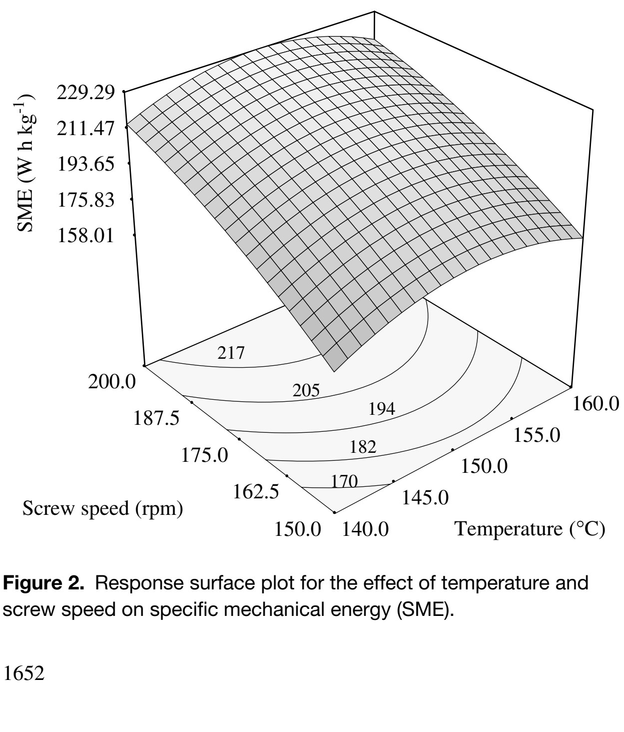

Figure 2. Response surface plot for the effect of temperature and screw speed on specific mechanical energy (SME).

Die pressure

The predicted model for die pressure (DP) can be described by the following equation in terms of coded values:

$$DP = 3749.41 - 385.61X_1 - 509.61X_1^2 \qquad (7)$$

ANOVA for the model as fitted (Table 3) shows significance ($P < 0.05$) with a significant lack of fit. The coefficient of variation (CV), which indicates the relative dispersion of the experimental points from the predictions of the model, was found to be 11.79% for die pressure. A reasonably good coefficient of determination ($R^2 = 0.7399$) and variation despite a significant lack of fit showed that the model developed for die pressure appeared to be adequate. It was observed that die pressure was significantly ($P < 0.05$) dependent on linear and quadratic terms of extrusion temperature. Screw speed did not affect significantly ($P > 0.05$) the die pressure. Similarly, Della Valle *et al.*[19] found no clear influence of screw speed on product die pressure. The values for die pressure in extrusion cooking of barley flour varied from 4196 to 1559 kPa. Die pressure decreased with an increase in temperature. The effects of extrusion temperature on die pressure are consistent with earlier published data.[20,21] The decrease in die pressure with increase in temperature may be attributed to the decrease in viscosity of molten barley.[16,20,22]

A negative correlation was also found between pressure and melt temperature ($R = -0.560$, $P < 0.05$) (Table 4), indicating that an increase in melt temperature tended to decrease the die pressure. The measured die melt temperature in extrusion cooking of barley flour ranged from 132 to 151 °C. The results agreed with those of previous studies which reported that the viscosity of molten polymers generally increases as temperature decreases; this would explain why the pressure at the die rises when the temperature is reduced.[19]

Expansion

The amount of expansion in food depends on the difference between the vapor pressure of water and the atmospheric pressure, as well as the ability of the exiting product to sustain expansion. The regression equation relating the response function

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Table 4. Correlation coefficients between product responses and system parameters

	SEI	BD	L	a	b	ΔE	PF	SME	DP	T
SEI	1	−0.145 n.s.	−0.341 n.s.	0.611*	0.663*	0.519 n.s.	−0.275 n.s.	0.294 n.s.	0.809**	−0.252 n.s.
BD		1	0.825**	−0.318 n.s.	−0.367 n.s.	−0.742**	0.984**	−0.225 n.s.	0.203 n.s.	−0.868**
L			1	−0.591*	−0.673*	−0.964**	0.815**	−0.326 n.s.	−0.197 n.s.	−0.637*
a				1	0.967**	0.701**	−0.365 n.s.	0.328 n.s.	0.503 n.s.	0.146 n.s.
b					1	0.804**	−0.415 n.s.	0.467 n.s.	0.592*	0.149 n.s.
ΔE						1	−0.760**	0.435 n.s.	0.380 n.s.	0.496 n.s.
PF							1	−0.279 n.s.	0.111 n.s.	−0.805**
SME								1	0.310 n.s.	0.132 n.s.
DP									1	−0.560*
T										1

SEI, sectional expansion index; BD, bulk density; ΔE, total color difference; PF, peak force; SME, specific mechanical energy; DP, die pressure; T, die melt temperature; * significant at $P < 0.05$; ** significant at $P < 0.01$; n.s., not significant.

expansion, measured as sectional expansion index and independent variable, was represented in terms of a coded variable by Eqn (8):

$$\mathrm{SEI} = 1.90 - 0.31X_1{}^2 \tag{8}$$

Regression analyses showed that SEI was significantly ($P < 0.001$) affected by the quadratic effect of temperature ($X_1{}^2$), whereas it was not significantly ($P > 0.05$) affected by screw speed (X_2). The response was analyzed using ANOVA and the data are presented in Table 3. The regression model for the influence of temperature (X_1) on SEI of extrusion of barley flour had a coefficient of determination (R^2) of 0.8210. The ANOVA showed that the quadratic model was significant ($P < 0.05$), whereas lack of fit was not significant ($P > 0.05$) for SEI.

The measured SEI of barley flour extrudates was between 1.042 and 2.109. The pressure drop when the cooked melt suddenly goes from high pressure to atmospheric pressure causes an extensive flash-off of internal moisture and water vapor pressure, which is nucleated to form bubbles in the molten extrudate, allows the expansion of the melt.[23] Moraru and Kokini[24] also reported that extrusion temperature plays an important role in changing the rheological properties of the extruded melts, which in turn affect the expansion volume. According to the quadratic effect of temperature, increasing temperature (above 150 °C) resulted in reduction in SEI of the extrudate. After a certain level, higher temperature could lead to lower SEI but not necessarily lower overall expansion because longitudinal expansion might increase. The latter especially can be significant when a slit-die is used, as a gradual pressure drop is encountered that could lead to nucleation of bubbles in the die and their growth along the longitudinal direction. Launay and Lisch[25] proposed that the longitudinal and sectional expansions are dependent on the melt viscosity and elasticity. The authors reported that an increased temperature would yield a lower melt viscosity and increased longitudinal expansion, while the melt viscosity would be lowered and cause a decrease in sectional expansion. Similar observations of the effect of temperature on product expansion were reported for corn starch, corn grits and rice flour by Chinnaswamy and Hanna,[26] Ali *et al.*[27] and Hagenimana *et al.*[28] Chinnaswamy and Hanna[26] found that expansion of corn starch increased as the barrel temperature increased from 110 to140 °C and declined with further increases in temperature. The increase in expansion of starch with temperature was attributed to its higher degree of gelatinization at such temperatures, while reduction in expansion was attributed to molecular degradation as reported by the authors. Surprisingly, screw speed had no significant effect on expansion. This was also observed by Ding *et al.*[29] in extrusion of rice. The lower die pressure indicating a lower melt viscosity was consistent with lower SEI. This could be supported by the positive correlation between SEI and die pressure ($R = 0.809$, $P < 0.01$) (Table 4). A similar correlation result has been observed in extrusion of corn grits.[30]

Bulk density

It is accepted that the SEI is not a sufficient criterion for expansion by itself under the tested extrusion conditions. Bulk density, expressed as g cm^{-3}, measures expansion too. The regression equation for bulk density as a function of temperature (X_1) was given in terms of coded variable by the following equation:

$$\mathrm{BD} = 0.46 - 0.30\mathrm{X}_1 + 0.12X_1{}^2 \tag{9}$$

ANOVA for the model of bulk density as fitted (Table 3) shows significance ($P < 0.05$) and the lack of fit is not significant ($P > 0.05$). The response surface regression model on bulk density yielded excellent fits with coefficient of determination ($R^2 = 0.9772$) for barley flour extrudates. Temperature (X_1) had a significant negative linear effect ($P < 0.001$), whereas its significant quadratic effect ($P < 0.001$) was positive.

Bulk density of barley flour extrudates varied widely between 0.259 and 1.069 g cm^{-3} based on the level of extrusion variables. The response surface (Fig. 3) shows that temperature had a dominant effect on bulk density, whereas screw speed seems to have a minor effect. Baik *et al.*[17] reported that the bulk density of barley extrudates was not significantly affected by screw speed. Bulk density values of barley flour extrudates decreased when temperature increased but at higher temperatures its quadratic effect dominated. Ding *et al.*[29] reported that an increase in barrel temperature would decrease melt viscosity and the reduced viscosity effect would favor bubble growth during extrusion. In addition, the degree of superheating of water in the extruder would increase at higher temperatures, also leading to greater expansion and hence gave a low bulk density proposed by the authors. By the positive quadratic effect of temperature, a high temperature would reduce the melt viscosity to a larger extent. This thin melt could facilitate bubble growth; however, the bubble walls become too thin to contain the vapor pressure, resulting in more bubble fracture, thus increasing the rate of collapse and resulting in an overall reduction in expansion.[31] The reduction of expansion caused an increase in bulk density. The highest bulk density value was obtained at lower temperatures. The same effect of temperature for bulk density was reported for extrusion of rice by Hagenimana *et al.*[28] Negative correlation was observed between bulk density and die melt temperature ($R = -0.868$, $P < 0.01$) as shown in Table 4.

Texture

The regression equations for peak force (PF), slope (S) and distance (Di) as textural attributes (measures of hardness, crispness and brittleness, respectively) were determined in terms of coded variables as follows:

$$PF = 8.17 - 8.74X_1 + 5.16{X_1}^2 \quad (10)$$

$$S = 8.52 - 4.85X_1 + 1.30{X_1}^2 \quad (11)$$

$$Di = 0.83 - 0.084X_1 + 0.21{X_1}^2 \quad (12)$$

ANOVA results for quadratic models of textural attributes are given in Table 3. Acceptable coefficient of determination values ($R^2 = 0.9844$, $R^2 = 0.9791$, $R^2 = 0.8462$) were obtained for significant models such as peak force, slope and distance with significant lack-of-fit variation. Although the lack of fit was significant, the coefficients of variation (CV) were found to be at the levels of 11.58%, 8.14% and 10.25% for peak force, slope and distance, respectively. On the basis of analysis of variance, the selected models adequately represented the data for textural attributes. Textural attributes (peak force, slope and distance) of extrudates were significantly ($P < 0.001$, $P < 0.001$, $P < 0.01$) dependent on linear and quadratic terms of temperature ($P < 0.001$). Screw speed had no significant ($P > 0.05$) effect on texture of extrudates. The influence of operating conditions on the changes in peak force of extrudates is shown in Fig. 4. Maximum peak force as measured by hardness of barley flour extrudates varied between 5 and 29 N. A decrease in product hardness with increasing temperature was observed. This is in agreement with the results of extrusion of wheat flour.[32] Yuliani *et al.*[31] reported that an increase in temperature would decrease the melt viscosity, causing more bubble growth and decreased bubble wall thickness, although some bubbles may collapse and fracture. This resulted in a lower bulk density and hence lower hardness of extrudates. The extrudate with the higher density would have relatively thicker cell walls and an overall lower porosity,[33] which is directly related to the hardness of samples. Agbisit *et al.*[34] observed an increase in cell diameter and decrease in cell number density with higher overall expansion. The authors found high negative correlations between mechanical properties and average cell diameter. Sacchetti *et al.*[35] reported a correlation between hardness and density of extruded cereal blend. These findings agree with the results of this study, as we found a positive correlation ($R = 0.984$, $P < 0.01$) between hardness and bulk density.

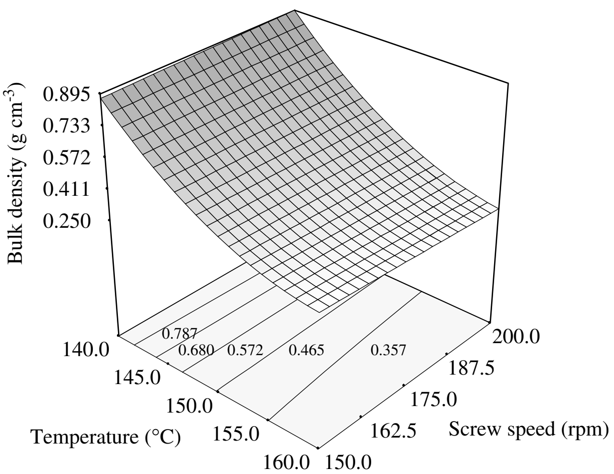

Figure 3. Response surface plot for the effect of screw speed and temperature on bulk density (BD).

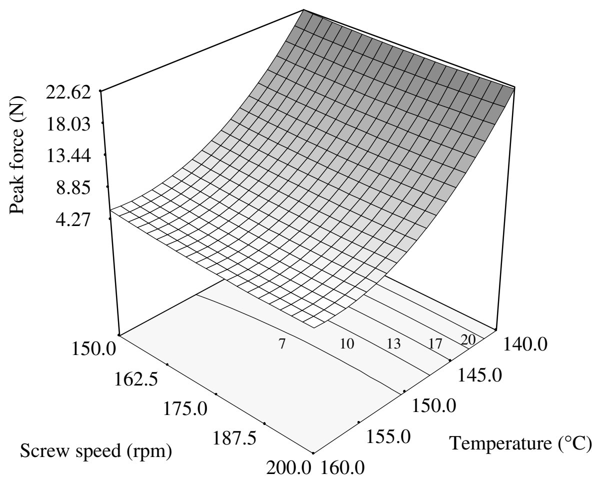

Figure 4. Response surface plot for the effect of temperature and screw speed on peak force (PF).

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Crispness is associated with a low-density cellular structure that is brittle and generates a high-pitched noise when fractured.[36] The slope of the force–distance curve before the first major fracturability peak was measured as the crispness of the extrudates.[14] The measured slope as crispness varied from 5 to 16 N mm^{-1} (data not shown). The lower the slope, the crispier is the product. The slope appeared to decrease with increasing temperature, indicating an increase in crispness. In this study, increasing temperature decreased peak force and bulk density of extrudates. Duizer and Winger[37] reported that less force is required in breaking a product that is very crisp. Therefore, crispness of extrudates was expected to increase with increasing temperature because it is related to the cellular structure of extrudates. Rayas-Duarte *et al.*[38] also stated that low breaking strength values are usually related to a large number of small cells per unit area with thinner cell walls, resulting in a crispy texture. Agbisit *et al.*[34] found that both average crushing force and crispness work had marked to high negative correlations with cell diameter. Both crushing force and crispness work increased with a decrease in cell diameter, indicating that more force and work were needed to deform/fracture smaller-size cells reported by authors.

The distance that is required in breaking extrudates, measured as brittleness, was determined, with the shortest distance being most brittle. The distance to break extrudates ranged between 0.74 and 1.23 mm. The effect of screw speed and temperature on distance is given in Fig. 5. Brittle behavior associated with crispness was mostly dependent on temperature. As temperature increased up to 150 °C, the distance was decreased and thus brittleness increased. However, further increase in temperature above 150 °C increased distance and therefore decreased brittleness. Increasing screw speed decreased distance but was not significant ($P > 0.05$). The most brittle product was obtained at 150 °C and a screw speed of 210 rpm. It was found that temperature was the main factor affecting the bulk density of the extrudates to a greater extent. It would be expected that low bulk density and low hardness value with increased temperature would produce a lower distance to break and thus higher brittleness of extrudates.

Color

Multiple regression equations for Hunter L color value and total color difference (ΔE) as a function of temperature (X_1) are given as follows:

$$\text{Hunter } L = 76.62 - 0.72X_1 \quad (13)$$

$$\Delta E = 5.98 + 0.60X_1 - 0.58{X_1}^2 \quad (14)$$

Hunter L value and ΔE were significantly affected only by temperature (X_1) ($P < 0.01$, $P < 0.05$, respectively). The effect of screw speed was not significant ($P > 0.05$). It was observed that the independent variables of temperature (X_1) and screw speed (X_2) did not influence significantly ($P > 0.05$) either Hunter a or b color value. Therefore, detailed analyses of the two color values are not presented. The significance of models of Hunter L value and ΔE is given in the ANOVA table (Table 3). Lack of fit was found to be non-significant ($P > 0.05$) for ΔE but significant ($P < 0.05$) for Hunter L color parameter. However, the Hunter L model gave a low coefficient of variation (CV = 0.81%), indicating that the experimental data were satisfactorily explained. The coefficients of determination (R^2) for the Hunter L color parameter and ΔE were 0.5469 and 0.7489, respectively. The Hunter L value reflects the lightness of samples: Hunter L value of barley flour was 80.95, whereas it varied between 74.93 and 77.88 for extruded samples. Hunter L color parameter of the barley flour extrudate decreased with increasing temperature. A similar effect of temperature on Hunter L value was found by Ilo and Berghofer[6] in extrusion cooking of maize grits. Hunter L value was negatively correlated with Hunter a value, Hunter b value and die melt temperature ($R = -0.591$, $R = -0.615$ and $R = -0.637$, respectively, $P < 0.05$) (Table 4). An increase in temperature caused a decrease in Hunter L value, possibly due to occurrence of browning reactions that increase Hunter a and b values. Hunter a value, indicative of the redness of sample with positive values, ranged between 2.06 and 3.02 for barley extrudates while barley flour had a Hunter a value of 1.75. The positive Hunter b value indicates the yellowness of the sample. The barley flour had a Hunter b value of 11.58, while the extruded barley samples had Hunter b values that ranged between 14.53 and 16.18. Hunter a and b values were strongly correlated with each other ($R = 0.967$, $P < 0.01$). ΔE of extrudates varied from 4 to 7. The effects of independent variables on ΔE are shown in Fig. 6. Increasing process temperature in extrusion cooking increased the rate of browning reactions, which increased the total color difference.[39] Although screw speed was not a significant independent variable

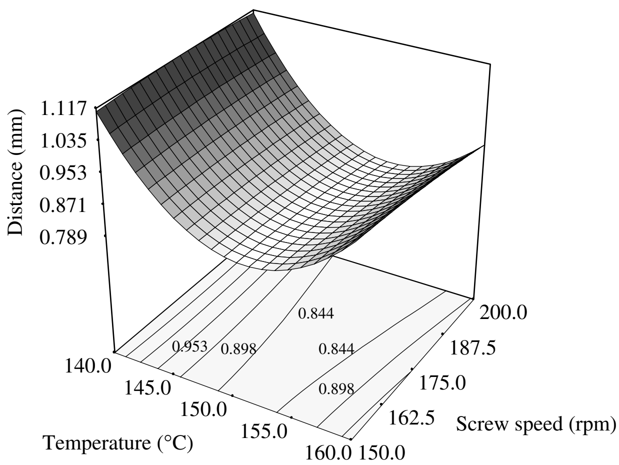

Figure 5. Response surface plot for the effect of screw speed and temperature on distance (*Di*).

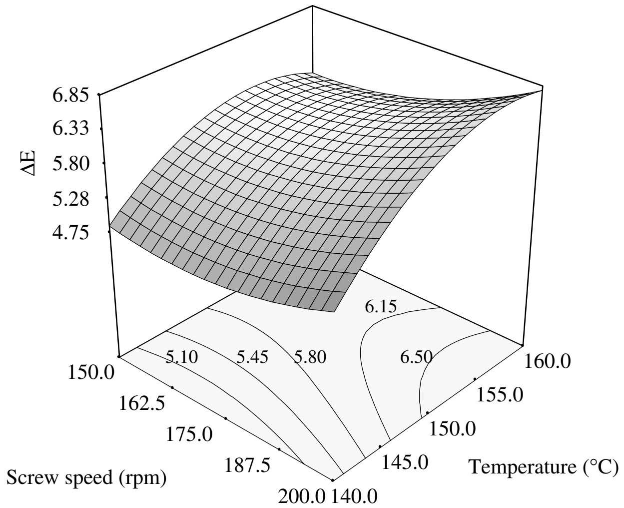

Figure 6. Response surface plot for the effect of temperature and screw speed on total color difference (ΔE).

(Eqn (14)), a slight increase in color difference with increasing screw speed was observed (Fig. 6).

Sensory analysis

Six extrudate samples that have acceptable textural properties (low hardness, high crispness and high brittleness) were selected out of 13 samples. Mean scores for sensory attributes of extrudates are given in Table 5. The appearance of extrudates was evaluated in terms of color and porosity. Sensory color of exrudates (A, B and C) produced at 150 °C with different screw speeds did not show significant ($P > 0.05$) difference and also extrudates (D and E) produced at 160 °C and at 150 and 200 rpm were not significantly different ($P > 0.05$). However, a significant difference ($P < 0.05$) was found between the extrudates produced at 150 °C and 160 °C (Table 5). The highest score (5.20) for porosity was obtained for extrudate D (160 °C, 150 rpm). Extrudate D was significantly ($P < 0.05$) different from extrudates A, B and C but not significantly ($P > 0.05$) different from extrudates E and F. Taste of extrudates was evaluated as bran flavor and bitterness. There was no significant difference among selected extrudates with respect to bran flavor as well as bitterness. Mean score for bran flavor was in the range 3.31–3.77. Sensory score for bitterness ranged from 1.62 to 2.00. The low score showed that panelists did not perceive any bitterness taste in any of the extrudates. As shown in Table 5, low scores of off-odor (1.54–1.88) were observed for all extrudates and were not significantly ($P > 0.05$) different.

The texture of extrudates was assessed in terms of hardness, crispness and brittleness. Extrudate D had the highest hardness score (4.83) compared to the other extrudates. It was significantly different ($P < 0.05$) from extrudates A, B and C but not significantly different ($P > 0.05$) from extrudates E and F. The higher sensory scores indicated that panelists preferred extrudates D, E and F compared to extrudates A, B and C with respect to hardness. Sensory hardness was negatively correlated with instrumentally measured peak force ($R = -0.833$) and slope ($R = -0.864$) values at $P < 0.05$ (Table 6). This means that increase in peak force (hardness) and slope (crispness), from the force–distance curve, caused a decrease in preference of panelists in hardness of extrudates. Sensory hardness was positively correlated with porosity ($R = 0.969$, $P < 0.01$). Panelists preferred extrudate D, with the highest score (5.44) for sensory crispness compared to all the extrudates, whereas it was not significantly ($P > 0.05$) different from exrudates E and F. Peak force measured instrumentally was positively correlated with slope as an indication of crispness. There was a negative correlation ($R = -0.817$, $P < 0.05$) between sensory crispness and slope measured as instrumental crispness, while a positive correlation ($R = 0.972$, $P < 0.01$) was observed between sensory crispness and sensory hardness. Sensory crispness was also positively correlated ($R = 0.970$, $P < 0.01$) with porosity.

Table 5. Mean scores for sensory attributes of extrudates produced by different extrusion conditions

	Extrudates					
Sensory attributes	A	B	C	D	E	F
Appearance						
Colour	4.05a	4.45a	4.14a	5.14b	5.37b	5.40b
Porosity	4.34a	4.25a	4.37a	5.20b	4.91ab	4.62ab
Taste						
Bran flavor	3.31a	3.77a	3.54a	3.45a	3.37a	3.31a
Bitterness	1.97a	1.97a	2.00a	1.62a	1.91a	1.85a
Off-odor	1.80a	1.71a	1.88a	1.60a	1.77a	1.54a
Texture						
Hardness	3.97ab	3.86a	4.00ab	4.83c	4.75bc	4.47abc
Crispness	4.22ab	3.94a	4.29abc	5.44d	4.97cd	4.88bcd
Brittleness	3.55a	3.27a	3.70a	5.05b	5.08b	5.00b
Overall acceptability	3.50a	3.75a	3.50a	5.69b	5.13b	5.47b

Means within a row with different lower-case letters are significantly different ($P < 0.05$).
A, 150 °C, 140 rpm; B, 150 °C, 175 rpm; C, 150 °C, 210 rpm; D, 160 °C, 150 rpm; E, 160 °C, 200 rpm; F, 164 °C, 150 rpm.

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Table 6. Correlation matrix between sensory attributes and textural properties of extrudates measured instrumentally

	Peak force	Slope	Distance	Sensory hardness	Sensory crispness	Sensory brittleness	Sensory color	Porosity	Overall acceptability
Peak force	1	0.907*	−0.402 n.s.	−0.833*	−0.809 n.s.	−0.824*	−0.785 n.s.	−0.805 n.s.	−0.794 n.s.
Slope		1	−0.700 n.s.	−0.864*	−0.817*	−0.914*	−0.966**	−0.772 n.s.	−0.931**
Distance			1	0.526 n.s.	0.562 n.s.	0.694 n.s.	0.760 n.s.	0.391 n.s.	0.763 n.s.
Sensory hardness				1	0.972**	0.965**	0.868*	0.969**	0.931**
Sensory crispness					1	0.943**	0.797 n.s.	0.970**	0.924**
Sensory brittleness						1	0.922**	0.883*	0.952**
Sensory color							1	0.755 n.s.	0.948**
Porosity								1	0.877*
Overall acceptability									1

* Significant at $P < 0.05$; ** significant at $P < 0.01$; n.s., not significant.

The expanded extrudate with low bulk density would have larger cells with thinner cell walls, resulting in a crispy texture and hence resulting in a low value of crispness force (slope) and high score of sensory crispness. Since the structure of extrudate becomes more open with larger cells, hardness decreases, color becomes brighter and it attracts higher sensory preferences. Dogan and Kokini[40] reported that crispness is associated with cellular foods in the glassy state, and structural parameters like porosity, pore size distribution, thickness and the strength of the cell wall and phase behavior are potentially important factors that affect mechanical behavior. Although the differences were not significant ($P > 0.05$) between extrudates D, E and F, extrudate E had the highest score (5.08) for sensory brittleness and extrudates A, B and C had lower scores (3.55, 3.27 and 3.70). Extrudates A, B and C were significantly different ($P < 0.05$) in sensory brittleness from extrudates D, E and F (Table 5). Sensory brittleness was negatively correlated with peak force ($R = -0.824$, $P < 0.05$) and slope ($R = -0.914$, $P < 0.05$) whereas it was positively correlated with sensory hardness ($R = 0.965$, $P < 0.01$) and sensory crispness ($R = 0.943$, $P < 0.01$) (Table 6). This means decreasing peak force and slope of extrudates increased preference of panelists in sensory brittleness as well as sensory hardness and sensory crispness. Sensory brittleness was also positively correlated with porosity ($R = 0.883$, $P < 0.05$). Extrudate D had the highest preference in terms of overall acceptability over other extrudates. Sensory scores for overall acceptability of extrudates A, B and C were significantly different ($P < 0.05$) from extrudates D, E and F (Table 5).

Overall acceptability of extrudates was positively correlated with sensory hardness ($R = 0.931$, $P < 0.01$), sensory crispness ($R = 0.924$, $P < 0.01$), sensory brittleness ($R = 0.952$, $P < 0.01$), sensory color ($R = 0.948$, $P < 0.01$) and porosity ($R = 0.877$, $P < 0.05$) but negatively correlated with slope ($R = -0.931$, $P < 0.01$).

Optimization

Optimization can be defined as the processing conditions that give the optimum (maximum or minimum) value of a function of certain decided variables subject to constraints that are imposed. Optimization may be the process maximizing a desired quantity or minimizing an undesired one. The values of the processing variables that produce the desired optimum value are called optimum conditions.[7] Product responses such as bulk density, texture and color were the most important major parameters determining quality of extrudates being consumed as snack foods. Therefore, optimum conditions for extrusion of barley flour were determined to obtain minimum bulk density, peak force (low hardness), slope (high crispness) and distance (high brittleness) and maximum Hunter L with minimum Hunter a values. To determine the optimum extrusion conditions, response surface of desirability function was used for numerical optimization. The desirability function of the response surface is shown in Fig. 7 for obtaining optimal conditions in extrusion cooking of barley flour. By applying the desirability function method, covering our criteria, one solution was obtained for the optimum conditions to produce barley extrudates. The desirability value obtained was 0.658. The optimum temperature and screw speed estimated were 156 °C and 166 rpm, respectively. By applying these optimal conditions, an edible barley extrudate with a bulk density equal to 0.332 g cm^{-3}, peak force (hardness) 4.99 N, slope (crispness) 6.25

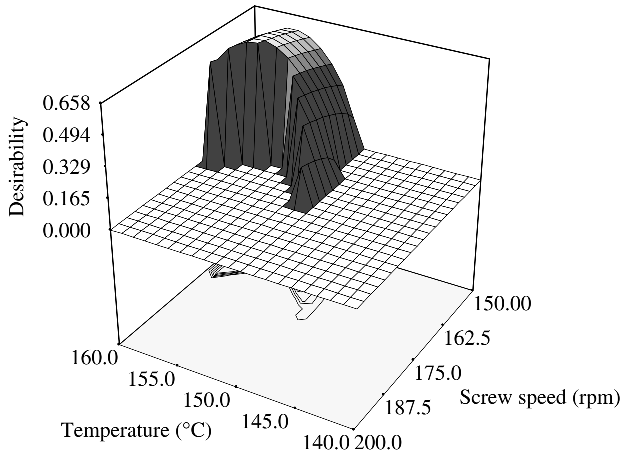

Figure 7. Desirability function response surface for barley flour extrudates.

N mm^{-1}, distance (brittleness) 0.86 mm, Hunter L 76.27, Hunter a 2.56, Hunter b 15.24 and ΔE of 6 could be produced.

CONCLUSION

Temperature had a more pronounced effect on system parameters and product responses than the screw speed. The effect of screw speed was significant for SME only. Extrudates produced under extrusion conditions of 160 °C, 150 and 200 rpm and of 164 °C with 150 rpm had higher preference levels of appearance, taste, texture and overall acceptability than that of other selected extrudates for sensory analysis. The optimal conditions for minimum bulk density and desired textural characteristics and color of extrudates correspond to a temperature of 156 °C and screw speed of 166 rpm. The use of barley flour in extruded snack products offers a desirable variation in diet and can take advantage of the nutritional quality of barley.

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