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System Parameters and Product Properties Responses During Extrusion of *Fura* from Millet-Soybean Mixtures

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ABSTRACT

A three-factor, three-level central composite rotatable composite design (CCRD) was adopted to study the effect of feed composition (X_1), feed moisture content (X_2) and screw speed (X_3) on the system parameters (torque, pressure, and specific mechanical energy) and fura extrudate properties (expansion ratio and bulk density) from blends of pearl millet and soybean flour mixtures. The torque was influenced negatively but significantly ($p < 0.05$) by linear effects of feed composition and screw speed. The die pressure was also influenced negatively by the linear effects of the screw speed significantly ($p < 0.05$). The response surface plot showed that the specific mechanical energy SME was decreasing as screw speed increased while SME marginally decreased as feed moisture increased. The linear effects of the independent variables significantly ($p < 0.05$) affected the expansion ratio. The linear and quadratic effects of the independent variables significantly ($p < 0.05$) affected the bulk density. The CCRD was effective in explaining the effect of the process conditions on *fura* as influenced by feed composition, feed moisture and screw speed. The importance of process variables on system parameters and physical properties could be ranked in the following order: Feed Composition (X_1) > Feed Moisture (X_2) > Screw Speed (X_3). Response variables predicted with model equations under optimum conditions were in general agreement with experimental data. The data obtained from the study could be used for control of product characteristics and possible projection for the commercial production of *fura*.

Keywords: Torque, pressure, specific mechanical energy, fura, soybean, extrusion, feed moisture, feed composition, screw speed.

Extrusion cooking technology has been widely used in the food industry to make a variety of products such as snack foods, baby foods, breakfast cereals, pasta and pet foods.

In order to maintain consistent product quality and improve productivity, it is crucial to optimize and properly control the extruder's operating conditions (Apruzzese *et al*., 2003). Extrusion cooking of formulated foods and food ingredients, protein and polysaccharide biopolymers and their mixtures, is an established unit operation in modern food processing (Shukula, 1991). Extrusion cooking technology is the most used technique for the production of snack foods (White, 1994; Meng *et al*., 2010). Extrusion is a powerful processing operation which utilizes highly expanded, low-density products with unique textural properties. Extrusion cookers are extremely difficult to model mechanistically due to the complex rheological properties and flow behaviour of the processed material, the poorly understood chemical reactions and the almost

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limitless screw and die configuration possible (Elsey *et al.*, 1997). Extrusion of foods demands close control of many variables such as feed moisture, feed composition, feed particle size, feed rate, barrel temperature, screw speed, screw configuration, die geometry, etc. The material properties and process variables determine the extent of macromolecular transformations during the extrusion process, which in turn influence the rheological properties of the food melt in the extruder and, consequently, the product characteristics of extrudates (Meng *et al.*, 2010). The effects of ingredient properties and processing conditions on final product quality are also reflected by their influence on process responses or extruder system parameters such as motor torque, die pressure, product temperature and specific mechanical energy (Meng *et al.*, 2010). The suitability of extruded foods for a particular application depends on their functional properties like water absorption, water solubility and oil absorption indexes, bulk density, expansion ratio, viscosity, etc. which are direct effects of system parameters, i.e. pressure, specific mechanical energy and torque. As extrudate properties are a result of different combinations of extrusion conditions such as feed moisture, screw speed and barrel temperature, system parameters could be used to describe or assess extrusion process under different operating conditions (Moraru and Kokini, 2003; Meng *et al.*, 2010). During extrusion, starch molecules undergo a variety of reactions that lead to a variety of transformations such as gelatinization, and molecular degradation due to the thermal and mechanical treatment resulting in series of changes that provoke loss of crystallinity, dissociation of the amylopectin double helices and leaching of the amylose. The extent of the physical and chemical changes may depend on the type of the starch, moisture levels in the feed stream, presence of other constituents, machine characteristics, residence time in the extruder and screw configuration. The rheological behaviour of a high moisture system is not expected to be the same as low or intermediate moisture extrusion systems. The distribution of shear, mixing, mechanical heat and convective heat may differ in a high moisture system compared to low or intermediate moisture system (Akdogan, 1996). The die is a major component in the extruder apparatus. Understanding the material properties and the nature of the flow in the extruder die is of primary importance in controlling the extruder performance and extrudate quality (Padmanabhan and Bhattacharya, 1989). Motor torque, commonly referred to as torque, provides a direct indication of the absorbed energy by the extruder screw and die orifice (Akdogan, 1996). Fluctuation in torque, and hence in energy, indicates erratic feeding, surging, and plugging. It is a very sensitive indicator during extruder operation (Fichtali and van de Voort, 1989).

Fura is one of the indigenous foods from cereals in the West African subregion. *Fura*, a traditional thick dough ball snack produced principally from pearl millet or sorghum, is very common in Northern Nigeria. The mode of preparation varies only slightly among different communities in the region, but the basic ingredient remains the same, that is millet or sorghum. It is traditionally consumed with *nono* (local yoghurt) or mashed in water before consumption in the form of porridge. Processing of *fura* has remained a home-based or artisanal activity that is carried out with rudimentary equipment and techniques, characterized by inconsistent product quality, poor hygiene, very short shelf life and unacceptable standards. Furthermore, the product lacks process specifications governing composition and ingredients. *Fura* has a limited storage life with a range of 3 – 4 days at refrigeration storage (5°C), 1 – 2 days at room temperature (25°C) and 18 hours at 35°C (Jideani *et al.*, 2002); being a single cereal-based product it is limiting in the essential amino acid lysine. Among all amino acids, lysine is the most limiting essential amino acid in cereal-based products, which are the majority of extruded products (Sin *et al.*, 2006). As a means of resolving issues related to malnutrition associated with the consumption of cereal based foods like fura in Nigeria, due to their low protein content, fortification of millet with soybean can go a long way in improving the protein quantity and quality of *fura* which is usually made from pearl millet solely. Interest in soybean foods has increased with consumer awareness of its health benefits, especially with soybean related ingredients being utilized as one of the major sources of high-protein fortification (United Soybean Board, 2006; Yeu *et al*., 2008). The production of *fura* through extrusion can further improve its physical state and functionality.

Modelling of extrusion processing involves a consideration of process parameters, system parameters, and product properties. Thus, extrusion cooking modelling is a multiple input and multiple output process. Though mathematical modelling of food extrusion process has benefited from available information on plastic extrusion, modelling of quality changes during food extrusion is a difficult task. Despite increased use of extrusion processing, extrusion is still a complicated process that has yet to be mastered. Small variations in processing conditions affect process variables as well as product quality (Qing-Bo Ding *et al*., 2005). Product quality can vary considerably depending on the extruder type, screw configuration, feed moisture and temperature profile in the barrel session, screw speed and feed rate.

The objective of this work was to study the effects of extrusion process conditions (feed composition, feed moisture and screw speed) on the toque, die presuure, specific mechanical energy (SME), bulk density (BD) and the expansion ratio (ER) during the extrusion of pearl millet-soybean flour mixtures using response surface methodology.

Materials and Methods

Flour preparation from millet

The process of flour preparation consists of dry cleaning of millet, i.e. winnowing using an aspirator Vegvari Ferenc (OB125, Hungary). The kernels were thereafter dehulled after mild wetting of the grain using a rice dehuller (India) at the Jimeta Main Market, Yola, Nigeria. After dehulling, the grains were washed and then dried in a Chirana convection oven model (HS 201A, Czech Republic) at 50°C for 24 h to 14% moisture content. The dried grain was milled using a Brabender roller mill (OHG DUISBURG model 279002, Germany) equipped with a 150 µm screen.

Flour preparation from soybean

The soybean seeds were steeped in tap water at 28°C for a period of 24 h in a plastic bowl. The kernels were thereafter dehulled using traditional pestle and mortar. After dehulling, the grains were washed and the hulls removed. The grains were thereafter dried in a Chirana convection oven model (HS 201A, Czech Republic) at 50°C for 24 h to 14% moisture content and the mass was winnowed to remove the remaining lighter materials using an aspirator Vegvari Ferenc (OB125, Hungary). The dehulled soybean kernels were ground in a laboratory disc mill (Nigeria) to fine flour. The flour was sieved using a150 µm screen, and the underflow was used for further research work.

Spice preparations

Kimba (Negro pepper) and ginger were sorted and cleaned manually before drying in a Chirana convection oven model (HS 201A, Czech Republic) at 60°C for 5 h. The seeds were then pounded using the traditional pestle and mortar. The mass was ground and sieved using a 150 µm screen size.

Blend preparations and moisture adjustment

Millet flour (MF) and soybean flour (SF) were mixed at various weight ratios, and the total moisture contents of the blends adjusted to the desired values with a mixer as described by Zasypkin and Tung-Ching Lee (1998). Weights of the components to be mixed were calculated using the following formula:

$$C_{SF} = \frac{[r_{sF} \text{ x } M \text{ x } (100 - W)]}{[100 \text{ x } (100 - W_{SF})]} \quad (1)$$

$$C_{MF} = \frac{[r_{MF} \text{ x } M \text{ x } (100 - W)]}{[100 \text{ x } (100 - W_{MF})]} \quad (2)$$

$$W_X = M - C_{SF} - C_{MF} \quad (3)$$

C_{SF} and C_{MF} are the masses of soybean flours (S_F) and millet flour (M_F), respectively, rSF or rMF are respective percentages of either soybean flours (S_F) or millet flour (M_F) in the blend, d.b.; ($r_F + r_{MF} = 100\%$); M is the total mass of the blend; w, the moisture content of the final blend, percentage wet weight basis (w.w.b.); WX is the weight of water added; and w_{SF} and w_{MF} are the moisture contents of S_F and M_F, respectively. The blends were mixed in a plastic bowl with the addition of the spices (Kimba and Ginger) at 1% level based on traditional formula; and the whole packed in polyethylene bags which was kept in the refrigerator overnight to allow moisture equilibration. The samples were however brought to room temperature before extrusion process.

Experimental design and data analysis

A three-factor central composite rotatable composite design [CCRD] (Box and Hunter, 1957) was adopted to study the effect of feed composition (X_1), feed moisture content (X_2) and screw speed (X_3) on the torgue, die pressure, specific mechanical energy (SME), expansion ratio (ER) and bulk density during extrusion of pearl millet and soybean flour mixtures for *fura* production. The independent variables and their variation levels are shown in Table 1. The levels of each variables were established according to literature information and preliminary trials. The outline of the experimental layout with the coded and natural values are presented in Table 2. Homogeneous variance is a necessary prerequisite for (linear) regression models. Therefore, a reduction in variability within the objective response (dependent variables) was by transforming the data to standardized scores $z = \frac{x - \overline{x}}{s}$ where x = dependent variable of interest; $\overline{x}$ = mean of dependent variable of interest and s = standard deviation). A quadratic polynomial regression model was assumed for predicting individual responses (Gacula and Singh, 1984; Wanasundara and Shahidi, 1996). The model proposed for each response of Y was $Y = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_{11} + X^2_1 + b_{22} + X^2_2 + b_{33} X^2_2 + b_{33} X^2_3 + b_{12} X_1X_2 + b_{12} X_1X_2 + b_{13} X_1 X_3 + b_{23} X_2X_3$ (4)

where Y = the response X_1 = Feed Composition, X_2 = Feed Moisture, X_3 = Screw Speed, b_0 = intercepts, b_1, b_2, b_3 are linear, b_{11}, b_{22}, b_{33} are quadratic and b_{12}, b_{13} and b_{23} are interaction regression coefficient terms. Coefficients of determination (R^2) were computed. The adequacy of the models was tested by separating the residual sum of squares into pure error and lack of fit. For each response, response surface plots were produced from the fitted quadratic equations, by holding the variable with the least effect on the response equal to a constant value, and changing the other two variables.

Table 1: Independent variables and levels used for central composite rotatable design[1]

		Coded variable level (x_i)				
Variable	**Symbol (X_i)**	**-1.68 (∝)**	**-1**	**0**	**1**	**1.68 (∝)**
Feed composition (%)	X_1	3.2	10	20	30	36.8
Feed moisture (%)	X_2	16.6	20	25	30	33.4
Screw speed (Rpm)	X_3	116	150	200	250	284

[1]Transformation of coded variable (x_i) levels to uncoded variables (X_i) levels could be obtained from $X_1 = 10x_1 + 20$; $X_2 = 5x_2 + 25$; $X_3 = 50x_3 + 200$

Extrusion cooking

Extrusion cooking was performed in a single screw extruder model (Brabender Duisburg DCE-330, Germany) equipped with a variable speed D-C drive unit, and strain gauge type torque meter. The screw has a linearly tapered rod and 20 equidistantly positioned flights. The extruder was fed manually through a screw operated conical hopper at a speed of 30 rpm which ensures the flights of the screw filled, thus avoiding accumulation of the material in the hopper. This type of feeding provides the close to maximal flow rate for the selected process parameters (barrel temperatures were 150^{o}C, 170^{o}C and 150^{o}C for the three heating zones respectively and 150^{o}C die temperature were maintained during extrusion; constant die and screw geometry but with three variable screw speeds) and three designed feed composition and feed moisture contents. A round channel die with separate infolding heater was used. The die used was a cone-shaped channel with 45 degrees entrance angle, a 3 mm diameter opening and 90 mm length. The screw was a 3:1 compression ratio. The inner barrel is provided with a grooved surface to ensure zero slip at the wall. The barrel is divided into two independent electrically heated zones, that is, feed end and central zone. There is a third zone at the die barrel, electrically heated but not air cooled. The extruder barrel has a 20 mm diameter with length to diameter ratio (L:D) of 20:1. Desired barrel temperature was maintained by a circulating tap water controlled by inbuilt thermostat and a temperature control unit. The feed material was fed into a hopper mounted vertically above the end of the extruder which is equipped with a screw rotated at variable speed. The rotating hopper screw kept feed zone completely filled to achieve a 'choke fed' condition. Experimental samples were collected when steady state was achieved, that is when the torque variation of ± 0.28 joules (₦m) or about 0.5% of full scale (Likmani *et al.*, 1991). The extrusion process consisted of 15 individual runs and conducted randomly.

Moisture content determination

Moisture content was determined in a Chirana convection oven model (HS 201A, Czech Republic) according to AOAC (1984).

Torque and die pressure

Torque and pressure were read directly from an inline strain gauge meter connected to the extruder which records the torque and pressure responses of material processing. Torque was recorded every 5 s for at least 10 min and average values expressed in Nm. Die pressure was measured using Dynisco pressure transducer. Readings were recorded every 5 s for at least 10 min and average values were expressed as kPa.

Specific mechanical energy (SME)

The specific mechanical energy was determined as described by Binoy *et al.* (1996) from the torque on the drive motor at constant screw speed and mass flow rate. In the extruder, this energy was provided by a 4.1 kW electric motor, which is coupled to the screw. SME (kJ/kg) was calculated using the following equation:

$$SME = \frac{n\ (actual) \times \%\ net\ torque \times P\ (rated)}{n\ (rated) \times 100 \times m} \quad (5)$$

Where n = screw speed (rpm); net torque = the measured torque less the lot frictional torque due to bearings and gear drive assembly; P = motor power (kJ/s); and m = feed rate (kg /s).

Expansion ratio (puff ratio)

Expansion ratio can be of two indices, diametral and longitudinal, as described by Sopade and Le Grys (1991). Diametral expansion is defined as the diameter of the extrudate whilst longitudinal expansion is defined as the length per unit dry weight. The diameter was determined after cooling of the extrudate; 10 samples were assessed for each extrudate and for each sample; diameters at three different positions were taken using vernier calipers and the result averaged. Expansion ratio expressed as the diameter of the extrudate to the diameter of the die.

Bulk density of extrudates

The bulk density (ρ) assuming cylindrical shape of extrudates was calculated using the method described by Ding *et al.* (2005) as follows:

$$\text{Density } (\rho) \quad (Kgm^{-3}) \quad (6)$$

where ρ is the bulk density of extrudate (Kgm^{-3}) with diameter D and L is the extrudate length per kilogram (m/kg). The samples were randomly selected and replicated 10 times and the average value taken.

Table 2: Experimental design extrusion experiment in their coded form and natural units[1, 2]

	Independent variables in coded form			Experimental variables in their natural units		
Design point	**(X_1)**	**(X_2)**	**(X_3)**	**(X_1)**	**(X_2)**	**(X_3)**
1	–1	–1	–1	10	20	150
2	–1	+1	–1	10	30	150
3	–1	–1	+1	10	20	250
4	–1	+1	+1	10	30	250
5	+1	–1	–1	30	20	150
6	+1	+1	–1	30	30	150
7	+1	–1	+1	30	20	250
8	+1	+1	+1	30	30	250
9	–1.68	0	0	3.2	25	200
10	+1.68	0	0	36.8	25	200
11	0	–1.68	0	20	16.6	200
12	0	+1.68	0	20	33.4	200
13	0	0	–1.68	20	25	116
14	0	0	+1.68	20	25	284
15	0	0	0	20	25	200

Responses[3]

Coefficient	**TORQUE**	**PRESSURE**	**SME**	**ER**	**BD**
Linear					
B_0	0.5989*	0.7611*	0.2522	–0.2424	0.2005
B_1	–0.0117	0.1097	0.0420	–0.2890*	0.2558*
B_2	–0.2601*	–0.1730	–0.0254	–1.0588*	1.0557*
B_3	–0.7184*	–0.5267*	–0.7689*	0.0722	–0.2084*
Quadratic					
b_{11}	-0.4477*	-0.6779*	-0.3444*	0.2251	–0.2652*

[1] Duplicate tests at all design point except the centre point (0, 0, 0) which was carried out five times and the result averaged.
[2] Experiment was carried out in randomized order; (X_1) = feed composition (%), (X_2) = feed moisture (%) and (X_3) = Screw speed (rpm)

Results and discussions

Torque

The measured mean experimental data for torque is presented in Table 3. The mean values for torque ranged from 13.98 – 30.86 ~~N~~m. A regression analysis was carried out to fit mathematical models to the experimental data. The regression coefficient for torque is presented in Table 4. The torque was influenced significantly ($p < 0.05$) by linear effects of feed composition and screw speed negatively suggesting that increase in both levels of feed moisture and screw speed resulted in decreased torque. The square term also showed negative significance ($p < 0.05$) influence both for feed composition and feed moisture on the torque. The quadratic influence of the screw speed on the torque was positive effect but was not significant ($p < 0.05$). The interaction effect of feed composition and feed moisture, and feed composition and screw speed had negative effects on the torque but was not significant ($p < 0.05$). Whereas the interaction effect of feed moisture and screw speed indicated negative influence on the torque. Examination of the model shows a good fit with $R^2 = 0.911$ for the torque. The shape of the 3-D plot for torque versus feed moisture and screw speed (Figure 1) indicated that increasing screw speed resulted in decrease in torque and decrease in feed moisture increased the torque. Guha *et al.* (2003) reported decrease in torque with increased in both feed moisture and screw speed during the extrusion cooking of rice. An increase in screw speed or decrease in feed rate reduces the degree of fill in the extruder causing torque to be at a low level (Guha *et al.*, 2003). The torque during extrusion usually decides the capacity of the extruder. Hsieh *et al.* (1990) reported lower screw speed generated significantly greater percentage of torque and die pressure of corn meal extruded with a twin screw extruder. They reported that screw speed was a more important determinant of percentage torque, specific energy and die pressure. Singh and Smith (1997) reported decrease in torque with increase in feed moisture and attributed it to reduced friction in the extruder as a result of increase in feed moisture. Guha *et al.* (1997) reported that increase in screw speed decreased the magnitude of torque due to (a) decrease in the filled length and (b) increase in the shear rate that reduces the apparent viscosity of the extrudate as the mass inside the extruder behaves as a pseudoplastic material (Harper, 1981; Bhattacharya *et al.*, 1992) that shows shear thinning behaviour. Yuliani *et al.* (2006) reported sharp decreases in torque with increasing screw speed, and gave a possible explanation that increasing screw speed at a constant feed rate would improve the pumping effect of the extruder screws leading to a decrease in barrel fill, resulting in a decrease in torque. Increasing screw speed would also induce shear thinning behaviour of starch melt, resulting in a reduction in melt viscosity, and consequently, the torque (Lu *et al.*, 1992).

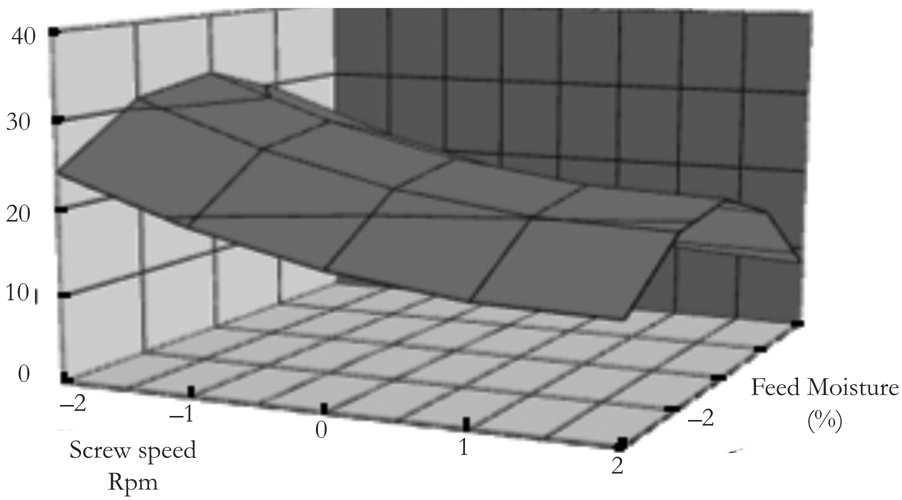


Figure 1: Response of the effect of Screw Speed and Feed Moisture on TORQUE

Die pressure

The measured mean experimental data for the die pressure is presented in Table 3. The mean values for the die pressure ranged from 1100 – 3370 kPa). A regression analysis was carried out to fit mathematical models to the experimental data for die pressure which is presented in Table 4. The die pressure was influenced positively by the linear effects of feed composition and feed moisture but was not significant ($p < 0.05$). Singh *et al.* (1998) reported decrease in the die pressure with increase in moisture content during extrusion of Monoglycerides and maize grits. However, the die pressure was influenced negatively by the linear effects of the screw speed significantly ($p < 0.05$). Yuliani *et al.* (2006) reported that die pressure decreased with the increase in screw speed. Increasing screw speed at a constant feed rate would reduce barrel fill and viscosity of the starch (result not shown) allowing it to flow more readily out of the die openings, reducing the buildup of die pressure. This is in agreement with Hsieh *et al.* (1993), Ryu and Ng (2001) and Yuliani *et al.* (2006) reported that high screw speed accelerated starch granules degradation, resulting in low viscous melt, and thus, decreased die pressure. The quadratic effects of feed composition and feed moisture indicated a negative significant ($p < 0.05$) effect on the die pressure, whereas the square term of screw speed showed positive effect on the die pressure but not significantly ($p < 0.05$). For the interaction term of feed composition and feed moisture on the pressure, it had positive significant ($p < 0.05$) effect on the die pressure. The interaction effect of feed composition and screw speed indicated negative effect on the pressure but not significantly ($p < 0.05$). However, the effect of the interaction of feed moisture and screw speed was positive on the die pressure but not significant ($p < 0.05$). Examination of the model shows a good fit with $R^2 = 0.934$ for the die pressure. The 3D plot shows that increasing the levels of both feed moisture content resulted in decreased die pressure (Figure 2).

Table 3: Experimental values for system parameters and extrudate physical properties[a]

Independent variables			Dependent variables				
X_1	X_2	X_3	TORQUE (Nm)	PRESS (kP_a)	SME ($KgKj^{-1}$)	ER (Ratio)	BD(gcm^{-3})
10	20	150	26.01	2620	456.34	2.64	0.165
10	30	150	21.81	1380	384.44	1.52	0.402
10	20	250	18.62	1840	373.11	2.52	0.117
10	30	250	13.98	1100	368.28	1.78	0.321
30	20	150	21.96	2230	389.48	2.36	0.164
30	30	150	22.31	2490	481.67	1.67	0.430
30	20	250	17.93	1040	383.61	2.48	0.181
30	30	250	17.83	1800	372.86	1.40	0.363
3.2	25	200	18.55	1130	388.76	2.37	0.174
36.8	25	200	18.38	1390	380.12	1.84	0.287
20	16.6	200	18.28	1760	383.16	2.45	0.190
20	33.4	200	14.67	1360	369.23	1.47	0.454
20	25	116	30.86	3370	598.36	1.81	0.295
20	25	284	20.89	2150	388.98	2.03	0.245
20	25	200	23.68	2590	419.02	1.89	0.294

[a] X_1 = Feed composition (%); X_2 = Feed moisture (%) and X_3 = Screw speed (rpm). PRESS = PRESSURE; SME = Specific mechanical energy; ER = expansion ratio; BD = Bulk density. Values are replicate averages. Standard deviation is not shown but replicate values were used for RSM analysis.

Table 4: Regression equation coefficients for objective responses[1,2]

Responses[3] Coefficient Linear	TORQUE	PRESSURE	SME	ER	BD
B_0	0.5989*	0.7611*	0.2522	– 0.2424	0.2005
B_1	– 0.0117	0.1097	0.0420	– 0.2890*	0.2558*
B_2	– 0.2601*	– 0.1730	– 0.0254	– 1.0588*	1.0557*
B_3	– 0.7184*	– 0.5267*	– 0.7689*	0.0722	– 0.2084*
Quadratic					
b_{11}	– 0.4477*	– 0.6779*	– 0.3444*	0.2251	– 0.2652*
b_{22}	– 0.6184*	– 0.5249*	– 0.3985*	0.0845	0.0853
b_{33}	0.1882	0.0872	0.3732*	0.0457	– 0.1139
Interaction					
b_{12}	0.2758	0.5398*	0.3666	0.0308	0.0095
b_{13}	0.2031	– 0.1440	– 0.0354	– 0.0993	0.1068
b_{23}	– 0.0269	0.1799	– 0.0831	– 0.0034	– 0.1581
R^2	0.934	0.911	0.826	0.9150	0.9639
Adjusted R^2	0.875	0.832	0.670	0.8384	0.9315
Lack of fit	*	*	*	*	*
Model	*	*	*	*	*

X_1 = Feed Composition, X_2 = Feed Moisture, X_3 = Screw Speed [2*]Significant at P < 0.05; NS, not significant
[3]PRESSURE; TORQUE; SME = Specific mechanical energy; ER = expansion ratio; BD = Bulk density

Specific mechanical energy (SME)

The specific mechanical energy (SME) is a good quantitative descriptor in extrusion processes and the amount of mechanical energy delivered to the extruded material determines the extent of macromolecular transformations and interactions that take place, i.e. starch conversion, and consequently, the rheological properties of the melt (Moraru and Kokini, 2003; Carvalho *et al.*, 2010). The mean value of the calculated specific mechanical energy (SME) of the extruded products is shown in Table 3. The mean value of the calculated SME ranged from 368.28 – 598.36 $KgKj^{-1}$. A regression analysis was carried out to fit mathematical models to the experimental data. Analysis of variance (table not shown) indicates that the linear and quadratic effects of the independent variables significantly ($p < 0.05$) affected the SME. The response equation coefficient for SME is presented in Table 4. The regression models for data were significant ($p < 0.05$) with satisfactory coefficients of $R^2 = 0.826$ for SME. The coefficients of variation (CV) were less than <10% (result not shown) suggesting the models could be reproducible (Montgomery, 1984). Examination of these parameters indicated that linear effect of screw speed and quadratic effects of feed composition and feed moisture had a significant ($p < 0.05$) decrease on SME. However, the quadratic effect of screw speed indicated an increase in SME. Increase in feed moisture resulted in decreased SME. Su and Kong (2007) reported a decrease in SME with increase in soybean oil during the extrusion of rice. It is good to note that in our study whole flour soybean was used which increased the fat content of feed resulting in decreased SME as amount of soybean was added. Increase in feed moisture during extrusion suggests reduction in viscosity which ultimately leads to reduced SME (Chang *et al.*, 1999; Hsieh *et al.*, 1989; Atlan *et al.*, 2008).

The amount of mechanical energy delivered to the extruded material plays a role in starch conversion. Higher SME usually results in a greater degree of starch gelatinization and extrudate expansion. Hence, increased SME is desired for expanding products. From the result of this study it shows that feed moisture and feed composition strongly influenced the SME, as expected, decreasing feed moisture resulted in increased SME. This agrees with the work reported by Kirby *et al.* (1988), Hu *et al.* (1993) and Singh *et al.* (1998). Choudhury and Gautan (2003) reported that increasing the amount of fish solids in the hydrolyzated fish muscle and rice blend resulted in lowering the SME input, reducing mixing and increasing the mean residence time. The power transmitted by the drive motor to the screws can be expressed as follows; which gives some insight into factors affecting SME during extrusion as described by Martelli (1983):

$$Z = f\left(\frac{Q^2 \mu \hat{u} N n^2}{K}\right) \quad (7)$$

Where Q = output (m^3/s); μ = melt viscosity in the filled channels (Nsm^{-2}); $\hat{u}$ = average viscosity in the filled channels (Nsm^{-2}); N = number of filled flights; n = screw speed (1/s); and K conductivity of the die (m^2). So if screw speed (n) is increased (by keeping feed rate constant) $Z \alpha n^2$ and $Z \alpha N$. It suggests that an increase in screw speed quadratically increases Z which means that the number of filled flights (N) reduces. Any decrease in N translates to a proportional decrease in Z. Other terms μ and $\hat{u}$ will be proportional to Z. As the extrusion feeds are pseudoplastic materials (Bhattacharya *et al.*, 1992; Guha *et al.*, 2003), it indicates that an increase in screw speed increases shear rate and subsequently decreases μ and $\hat{u}$. The net result will be decrease in Z and consequently decrease in SME.

The response surface plot (Figure 3.) shows that the specific mechanical energy (SME) was decreasing as screw speed increased while SME marginally decreased as feed composition increased. Contrary to our study, Altan *et al.* (2009) reported that SME decreased with increasing temperature and decreasing screw speed during the extrusion of barley-tomato pomace blends. The variation of their report with this study might be attributed to the differences in the materials used and, in addition, temperature was kept constant for our study, and more so, lubricating effect possibly contributed by the oil in soybean might have reduced the viscosity and consequently the shear effect. Baik *et al.* (2004) reported that increasing the screw speed causes increase in SME input attributed to the increase in shear rate with increased screw speed. Janes (1993) reported that in general, adding about 0.5 % vegetable oil to a cereal-based mixture significantly decreases the SME input in the low moisture extrusion cooking, if the other extrusion variables are kept constant. Altan *et al.* (2009) reported that SME depended on the type of raw material used and screw configuration. Decrease in SME with increasing moisture content for this study was in agreement with the findings of other workers obtained during extrusion processing of starch based materials (Antila, *et al.*, 1983; Meuser and van Lengerich, 1984a, b; Meuser *et al.*, 1985, 1987; Senouci and Smith, 1986; Mange and Boissonant, 1987; Della Valle *et al.*, 1989). It can be inferred that combined dual effects of water and oil from the soybean flour decreased the viscosity which lowered the shear effect, leading to drop in the SME. Feed moisture is a key factor in determining flow properties of food dough during extrusion cooking. Increased feed moisture decreases the viscosity of a food dough (as indicated by lowered die pressure) and reduces the rotating friction of the screws, which is translated into lowered torque (Govindasamy *et al.*, 1997). Lubricating effects of water lowers the SME input. Viscosity of the starch mass and its ability to dissipate mechanical energy decreases when the water content is high.

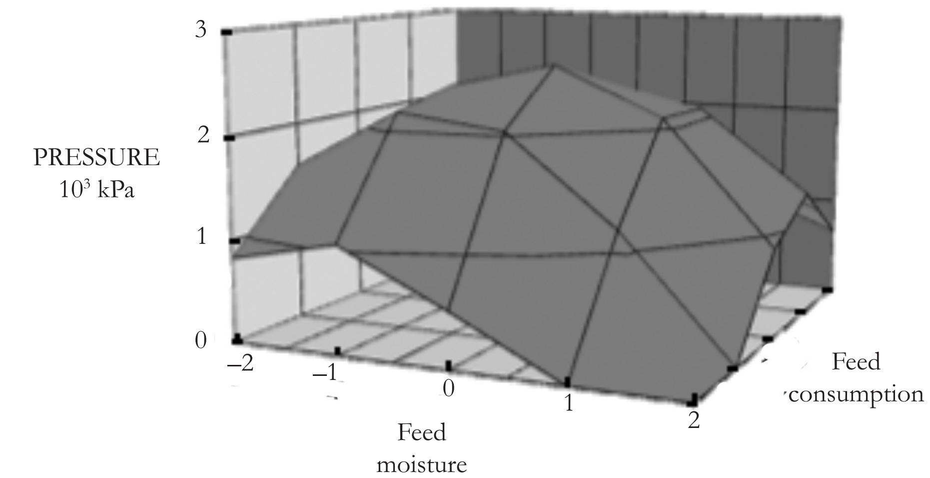


Figure 2: Response of the effect of Feed Moisture and Feed Composition on PRESSURE

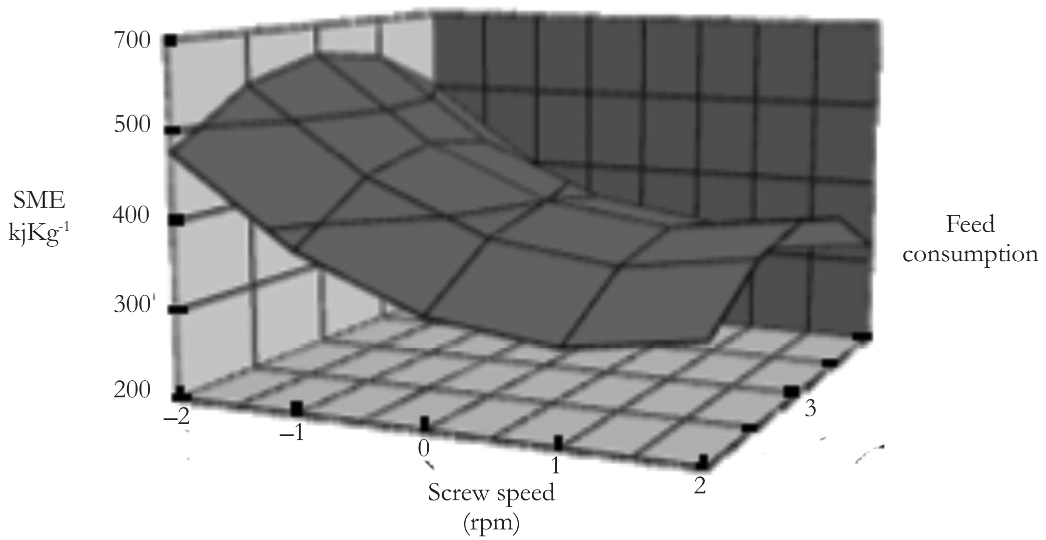


Figure 3: Response effect of Screw Speed and Feed Composition on SME

Expansion ratio (ER)

The mean experimental values of expansion ratios (ER) of the extruded products are shown in Table 3. The mean experimental values of expansion ratio ranged from 1.40 – 2.64. Analysis of variance (table not shown) indicates that only the linear effects of the independent variables significantly ($p < 0.05$) affected the expansion ratio. The response equation coefficient for ER is presented in Table 4. The models showed good fit with adjusted R^2 = 0.0.83 for ER. This suggests a very good fit to the experimental data and the model could be used to describe the process. The negative significant ($p < 0.05$) linear coefficients of feed composition and feed moisture indicated that their effects on ER were a decrease. Moisture plays a key role in the mechanism responsible for expansion. The 3D plot (Figure 4) shows that increasing feed moisture resulted in decreased ER. The same plot indicated that increasing the amount of soybean flour indicated decrease in the ER. Considering the elastic properties of the amylopectin network as being responsible for diametral expansion is helpful in explaining such role of moisture. This is a commonly observed phenomenon in many extruded foods, which can be attributed to the fact that the amount of expansion in a food material depends on pressure differential between the die and the atmosphere.

Food with lower moisture content tend to be more viscous than those having higher moisture content and therefore the pressure differential is smaller for higher moisture foods leading to a less expanded product. However, increasing screw speed resulted in increase in ER (result not shown). Increasing screw speed tends to increase the shearing effect; this causes protein molecules to be stretched farther apart, weakening bonds and resulting in a puffer product. Harmann and Harper (1973) postulated two factors in governing expansion: (a) dough viscosity, and (b) elastic force (die swell in the extrudate. The elastic forces will be dominant at low moisture and temperature. The bubble growth, which is driven by the pressure difference between the interior of the growing bubble and atmospheric pressure resisted primarily by the viscosity of the bubble wall, dominates the expansion at high moisture content high temperature (Panmanabhan and Bhattacharyya, 1989). A viscoelastic melt in a food extruder expands due to flashing of moisture at the die exit. The expansion process can be described as nucleation in the die, extrudate swelling immediately beyond the die, followed by bubble growth and collapse (Kokini *et al*., 1991). Increased water content in the melt would soften the amylopectin molecular structure and reduce its elastic characteristics to decrease diametral expansion (Avarez-Martinez *et al*., 1988). In addition, increased level of soybean flour marginally decreased expansion ratio, which is expected, because of the high fat in the soybean flour. Feed moisture has been identified as the main factor affecting extrudate expansion and density (Faubion and Hosney, 1982; Harper and Tribelhorn, 1992; Gujral *et al*., 2001). Extrudates can expand in both the cross-sectional (diametrical) direction and the longitudinal direction (Launary and Lisch, 1983). A porous, expanded, sponge-like structure is formed inside extrudates as a result of many tiny steam bubbles created by the rapid release of pressure after exiting the die (Conway, 1971). Increased feed moisture during extrusion would provoke change in the amylopectin molecular structure of the material reducing the melt elasticity, thus decreasing the expansion and increasing the density of extrudate (Qing-Bo *et al*., 2005).

A puffer extrudate resulted by decreasing the lipid content in the feed mix (Bhattacharya and Hamma, 1988). Singh *et al.* (2007) reported decrease in ER with increase in feed moisture of rice-pea grits extrudates. Extruded snacks possess the typical texture of puffed, light and crispy. Some physical properties of extruded snack were reported including bulk density of 48 – 64 g/l, 50 – 160 g/l (Moore, 1994) and 59 10 g/l (Boonyasirikool *et al*., 1996) and expansion ratio of 3.06 – 3.83 (Mohamed, 1990) and 4.03 (Boonyasirikool *et al*., 1996). Seker (2005) reported that increasing screw speed improved sectional expansion and reduced bulk density of extrudate during extrusion of soybean protein and corn starch. He further reported that mixtures of soybean protein isolate/modified starch had higher sectional expansion indices than those of native starch/soybean protein isolate, indicating that feed materials (in addition to phase transition) may contribute to the reduced expansion of extrudate containing soybean protein. Modified starch/soybean protein isolate mixtures, had lower bulk densities than native starch/soybean protein isolate mixtures, and it is suggested that bulk densities of extrudate containing high levels of soybean protein can be reduced by inclusion of cross linked starch in the extrusion mix. Chaiyakul *et al.* (2009) reported that expansion was greatest for low protein, low moisture and high temperatures during the extrusion of high protein glutinous rice-based snack. These relationships have been reported elsewhere for corn and wheat-based snacks (Bhattacharya and Hanna, 1987; Chinnaswamy and Hanna, 1990; Faubion and Hosney, 1982; Ilo *et al.,* 1999). Filli and Nkama (2007) reported that pearl

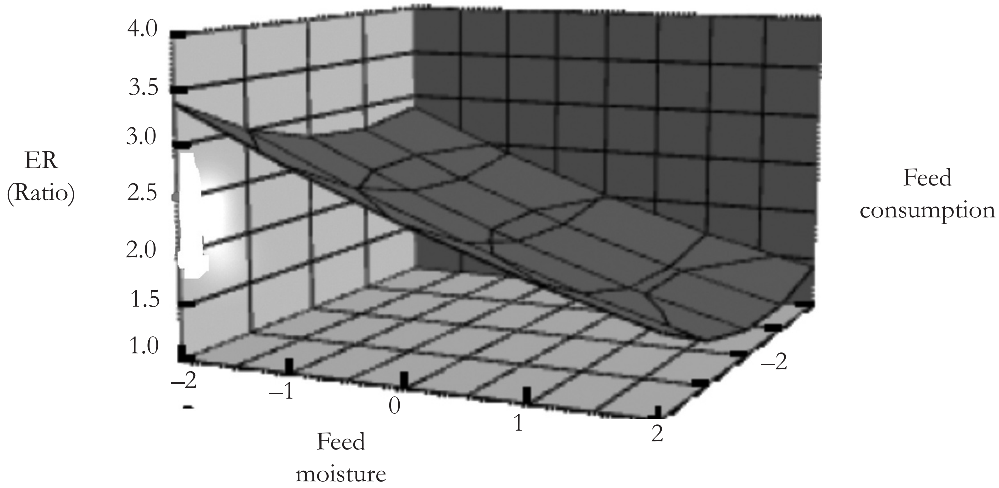


Figure 4: Effect of Feed Moisture and Feed Composition on ER

millet: cowpea *fura* (80:20) had the highest puff ratio of 4.71 while the pearl millet: groundnut (70:30) *fura* had the least puff ratio of 2.90.

Bulk density (BD)

The mean values of bulk density (BD) of the extruded products are shown in Table 3. Bulk density measures the total volume of the extrudates, indicating the extent of expansion. The experimental mean value of BD varied from 0.12 – 0.47 gcm^{-3}. Analysis of variance (table not shown) indicates that the linear and quadratic effects of the independent variables significantly ($p < 0.05$) affected the bulk density. The response equation coefficient for BD is presented in Table 4. The models showed good fit with adjusted $R^2 = 0.93$ for BD. This suggests a very good fit to the experimental data and the model could be used to describe the process. The positive significant ($p < 0.05$) linear coefficients of feed composition, feed moisture and screw speed indicated that their effects on BD were an increase. However, the negative significant ($p < 0.05$) coefficients linear effect of screw speed and quadratic interaction of feed composition resulted in a decrease in BD. The 3D surface plot for BD (Figure 5.) indicates that feed composition and screw speed appeared to significantly influence the bulk density (BD). Increasing the level of soybean flour resulted in increased BD, while the BD decreased as a result of increased screw speed marginally. Feed moisture influenced BD significantly and increasing feed moisture resulted in increased BD (result not shown).

Hagenimana *et al.* (2006) reported that the BD increased with increase in moisture content during the extrusion of rice flour. Traditionally, extrudate expansion has been expressed in terms of radial enlargement and decrease in density which have been correlated with changes in melt moisture and temperature. Bulk density is a measure of how much expansion has occurred as a result of extrusion. The heat developed during extrusion can increase the temperature of the moisture above the boiling point so that when the extrudate exits from the die, a part of the moisture would quickly flash off as steam and result in an expanded structure with large alveoli and low bulk density. On the other hand, if not enough heat is generated to flash-off enough of the moisture (either through low process temperature or high feed moisture), less expansion occurs resulting in a high bulk density product with collapsed cells which usually disintegrates on cooling. High bulk density product is an indication of more uniform and continuous protein matrix and, therefore, the extrudate is dense with parallel layers, no air pockets and is not spongy upon hydration (Taranto *et al.,* 1978). Qing-Bo *et al.* (2005) and Meng *et al.* (2010) reported extrudate density to be most depended on feed moisture, increased feed moisture lead to sharp increase of extrudate density. Screw speed was observed to have slight impact on the density of extrudate. High bulk density product is an indication of more uniform and continuous protein matrix and therefore, the extrudate is dense with parallel layers, no air pockets and is not spongy upon hydration (Taranto *et al.*, 1978).

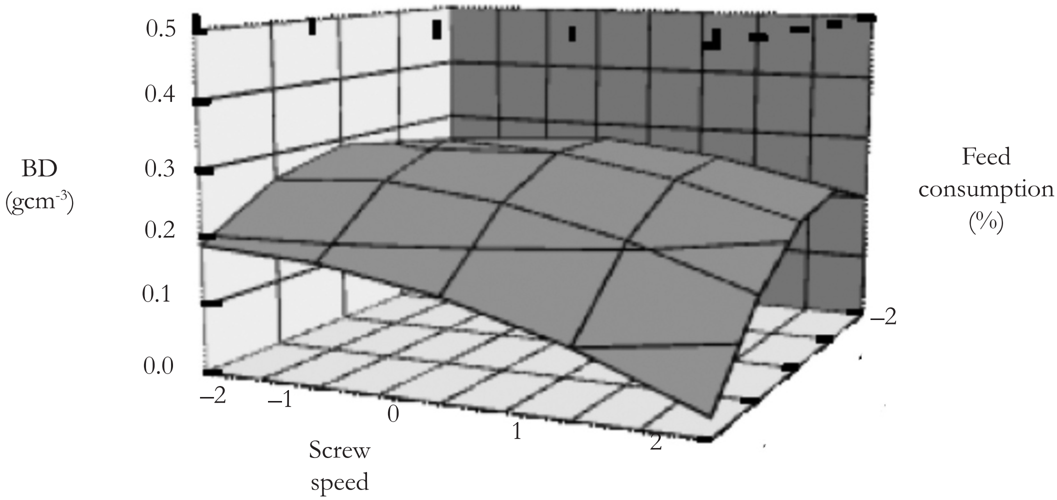


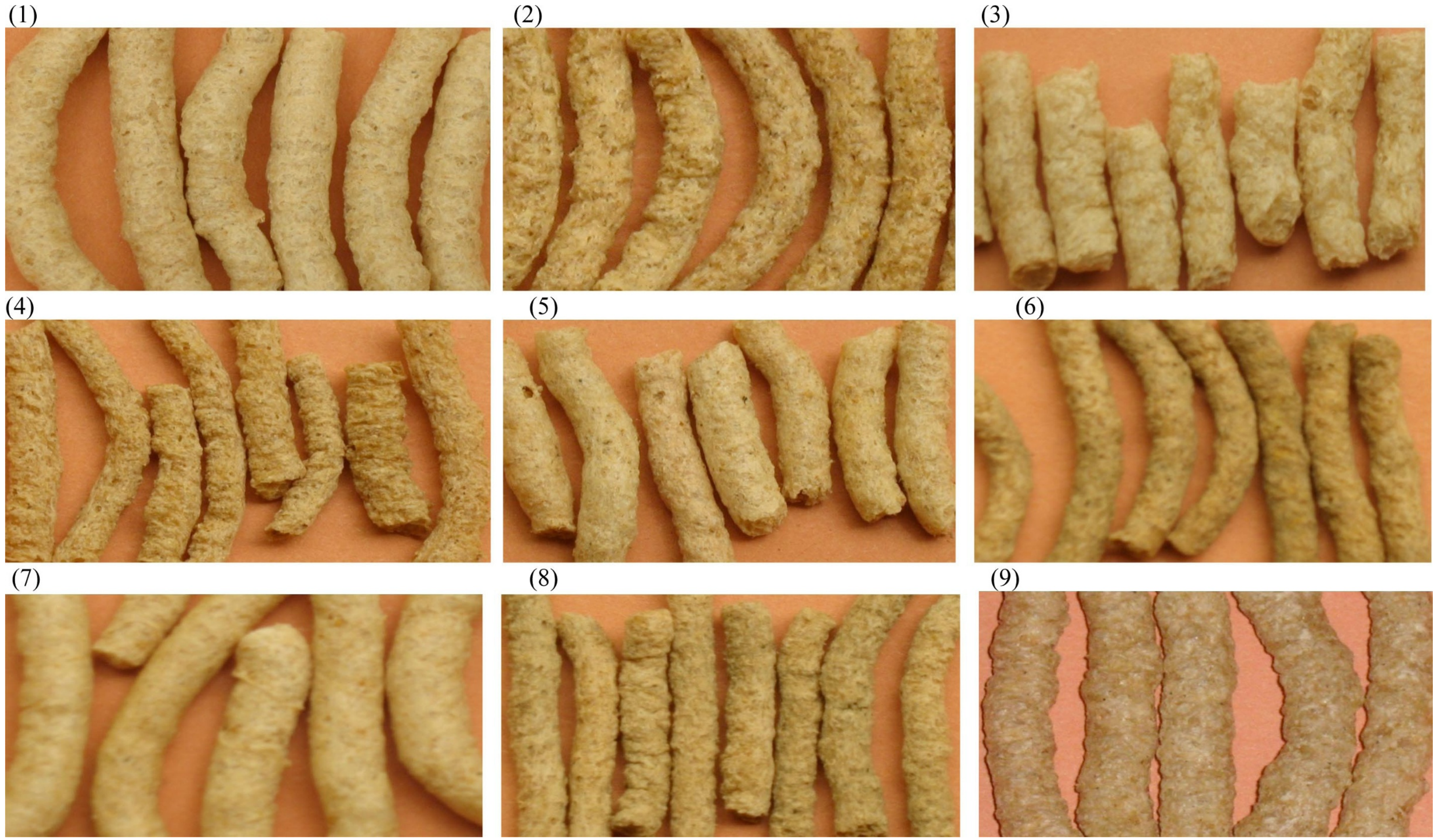
Figure 5: Effect of Screw Speed and Feed Composition on BD

Extrudate photographic responses

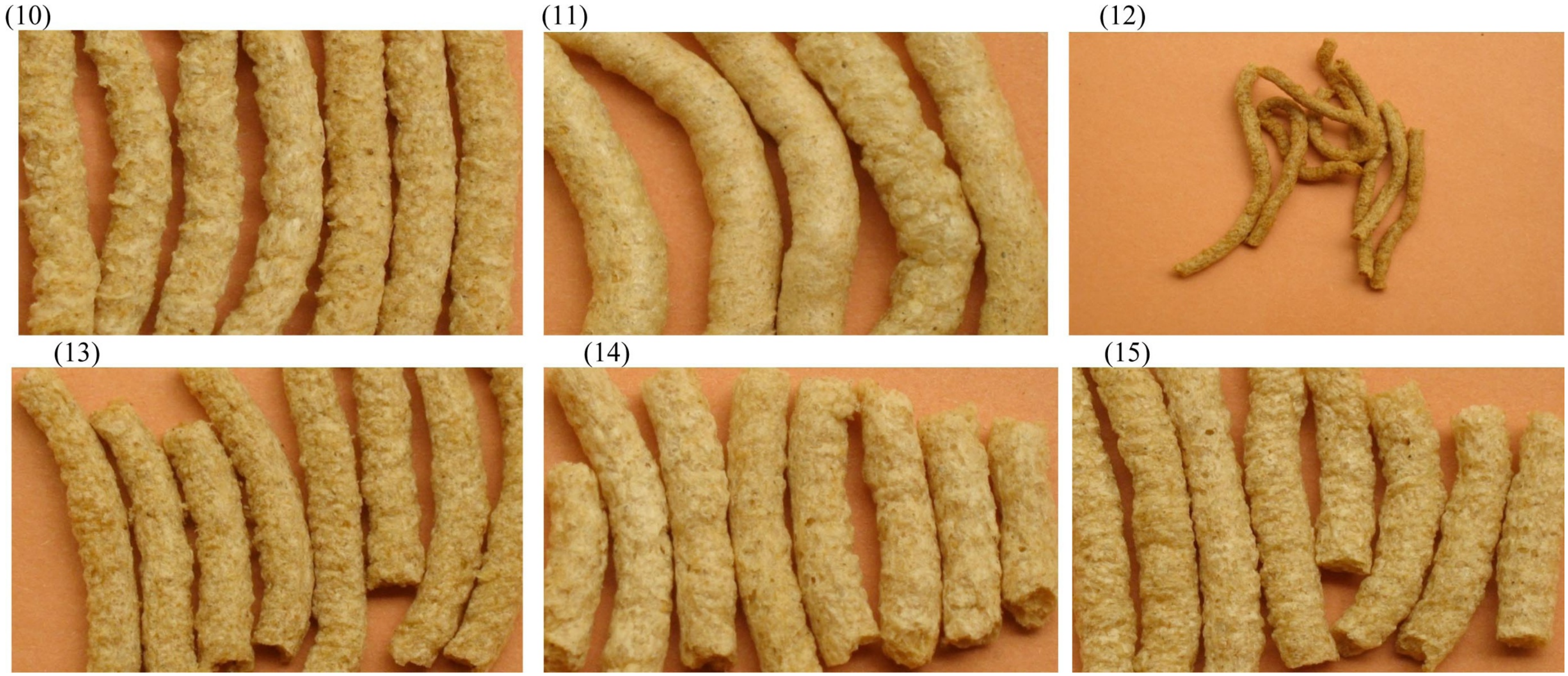
The effects of extrusion variables (feed composition, feed moisture and screw speed) can be seen as shown in Plates 1 – 15. The effect of the independent variables on the expansion ratio of extrudates is evident. The results shown in the photographs describe the changes that occurred during extrusion as influenced by the extrusion variables.

Conclusion

The pressure was influenced positively by the linear effects of feed composition and feed moisture but was not significant ($p < 0.05$). The torque was influenced significantly ($p < 0.05$) by linear effects of feed composition and screw speed negatively suggesting that increase in both levels of feed moisture and screw speed resulted in decreased torque. The specific mechanical energy SME was decreasing as screw speed increased while SME marginally decreased as feed moisture increased. Increasing the amount of soybean flour and extrusion feed moisture resulted in decreased the ER. The linear and quadratic effects of the independent variables significantly ($p < 0.05$) affected the bulk density. The models showed good fit with adjusted $R^2 = 0.93$ for BD. This suggests a very good fit to the experimental data and the model could be used to describe the process. The positive significant ($p < 0.05$) linear coefficients of feed composition, feed moisture and screw speed indicated that their effect on BD were an increase. Results indicated that the variables were significant on the torque, pressure specific mechanical energy (SME), expansion ratio (ER) and bulk density (BD). The importance of process variables on target parameters could be ranked in the following order: Feed moisture (X_1) > Feed composition (X_2) > Screw speed (X_3).



Plates 1 – 9: **Shows the physical state of extrudate responses: (1) 10% soybean, 20% feed moisture, 150 rpm screw speed; (2) 10% soybean, 30% moisture, 150 rpm screw speed; (3) 10% soybean, 20% feed moisture, 250 rpm screw speed; (4) 10% soybean, 30% feed moisture, 250rpm screw speed; (5) 30% soybean, 20% feed moisture, 150rpm screw speed; (6) 30% soybean, 30% feed moisture, 150 rpm screw speed; (7) 30% soybean, 20% feed moisture, 250 rpm screw speed; (8) 30% soybean, 30% feed moisture, 250 rpm screw speed; (9) 3.2% soybean, 25% feed moisture, 200 rpm screw speed.**



Plates 10 – 15: Shows the physical state of extrudate responses (continues) (10) 36.8% soybean, 25% feed moisture, 200 rpm screw speed; (11) 20% soybean, 16.6% feed moisture, 200 rpm screw speed; (12) 20% soybean, 33.4% moisture, 200 rpm screw speed; (13)20% soybean, 25% feed moisture, 116 rpm screw speed; (14) 20% soybean, 25%, feed moisture, 284 rpm screw speed; (15) 20% soybean, and 25% feed moisture, 200 rpm screw speed

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References

Akdogan, H. (1996). Pressure, torque and energy responses of a twin screw extruder at high moisture contents. *Food Research International* 29 (5 – 6): 423 – 429.

Apruzzese, F., Pato, J., Balke, S.T. and Diosady, L.L. (2003). In-Line measurement of residence time distribution in a co-rotating twin-screw extruder. *Food Research International* 36: 461 – 467.

Altan, A. McCarthy, K.L., and Maskan M. (2008). Evaluation of snack foods from barley-tomato pomace blends by extrusion processing. *Journal of Food Engineering* 84: 231 – 242.

Altan, A. McCarthy, K.L. and Maskan, M. (2009). Effect of screw configuration and raw material on some properties of barley extrudates. *Journal of Food Engineering* 92: 377 – 382.

Alvarez – Martinez, L., Kondury, K.P., and Harper, J.M. (1998). A general model for expansion of extruded products. *Journal of Food Engineering* 53: 609 – 615.

Antila, J., Eiler, K. and Linko, P. (1983). Production of flat bread by extrusion cooking using different wheat/rye ratios, protein enrichment and grain with poor baking ability. *Journal of Food Engineering* 2: 189 – 210.

AOAC (1984). *Official Method of Analysis*. 14th ed. Association of Official Analytical Chemists, Washington D.C.

Baik, B.K., Powers, J., and Nguyen, L.T. (2004). Extrusion of regular and waxy barley flours for production of expanded cereals. *Cereal Chemistry* 81: 94 – 99.

Bhattacharya, M. and Hanna, M.A. (1987). Influence of process and product variables and extrusion energy and pressure requirements. *Journal of Food Engineering* 6: 153 – 163.

Bhattacharya, M. and Hanna, M.A. (1988). Effect of Lipids on the properties of extruded products. *J. Food Sci.* 53: 764 – 766.

Bhattacharya, S., Das, H., and Bose, A.N. (1992). Rheological behaviour during extrusion of blends of minced fish and wheat flour. *Journal of Food Engineering* 15: 123 – 137.

Binoy, K.G., Aaron, J.O. and Gour, S.C. (1996). Reverse screw element(s) and feed composition effects during twin-screw extrusion of ice flour and fish muscle blends. *J. Food Sci.*, 61 (3): 590 – 595.

Boonyasirikool, P., Charunuch and Phongpipatpong, M. (1996). Production of bean snack by twin-extruder. *Food in Thai*. 26 (1): 14 – 33.

Box, G.E.P. and Hunter, J.S. (1957). Multifactor experimental design for exploring response surfaces. *Annals Math. Stat.* 28: 195 – 242.

Carvalho, C. W. P., Takeiti, C. Y., Onwulata, C. I. and Pordesimo, L.O. (2010). Relative effect of particle size on the physical properties of corn meal extrudates: Effect of particle size on the extrusion of corn meal. *Journal of Food Engineering* 98: 10 –- 109

Chang, Y.K., Marttinez-Bustos, F., Park, T.S. and Kokini, J.L. (1999). The influence of specific mechanical energy on cornmeal viscosity measured by an on-line system during twin-screw extrusion. *Brazilian Journal of Chemical Engineering* 16: 285 – 295.

Chinnaswamy, R. and Hanna, M.A. (1990). Relationship between viscosity and expansion properties of various extrusion-cooked grain components. *Food Hydrocolloids* 3: 423 – 434.

Chiyakul, S., Jangchud, K., Janchud, A., Wuttijumnong, P. and Winger, R. (2009). Effect of extrusion conditions on physical and chemical properties of high protein glutinous rice-based snack. *LWT Food Science and Technology* 42: 781 – 787.

Choudhury, G.S. and Gautam, A. (2003). Effects of hydrolysed fish muscle on intermediate process variables during twin-screw extrusion of rice flour. *Lebensmittel-und-technologie* 36: 667 – 678.

Conway, H.F. (1971). Extrusion cooking of cereals and soybeans. *I. Food Product Development* 5 (27): 29 – 31.

Della Valle, G., KKozlowski, Colonaa, P. and Tayeb, J. (1989). Starch transformation estimated by energy balance on a twin screw extruder. *Lebensm. Wiss. u. Technol.* 22: 279 – 286.

Elsey, J., Riepenhausen, J., McKay, B., Barton, G. W., and Willis, M. (1997). Modeling and control of food extrusion process. *Computers and Chemical Engineering* 21: S361 – 366.

Faubion, J.M. and Hoseney, R.C. (1982). High temperature short time extrusion cooking of wheat starch and flour. 1: role of moisture and flour type in the production of extrudates. *Cereal Chemistry* 59: 533 – 543.

Fichtali, J. and van de Voort, F. R. (1989). Fundamental and practical aspects of twin screw extrusion. *Cereal Foods World* 34 (11): 921 – 929.

Filli, K.B. and Nkama, I. (2007). Hydration properties of extruded fura from millet and legumes. *British Food Journal* 109 (1): 68 – 80.

Gacula, (Jr) M.C. and Singh, J. (1984). *Statistical Methods in Food and Consumer Research*. Academic Press, Inc., New York, pp. 214 – 272.

Govindasamy, S., Campanella, O.H. and Oates, C.G. (1997). High moisture twin srew extrusion of sago starch.II. Saccharification as influenced by thermo mechanical history. *Carbohydrates Polymers* 32: 267 – 274.

Guha, M., Ali, S.Z., and Bhattacharya, S. (1997). Twin-screw extrusion of rice flour without a die: Effect of barrel temperature and screw speed on extrusion and extrudate characteristics. *Journal of Food Engineering* 32: 251 – 267.

Guha, M., Ali, Z.S. and Bhattacharya, S. (2003). Screening of variables for extrusion of rice flour employing a Plackett-Burman design. *Journal of Food Engineering* 57: 135 – 144. Harper, J. M. (1981). *Extrusion of Food* Vol. 2. CRC Press, Boca Raton, Fl.

Gujral, H.S., Singh, N. and Singh, B. (2001). Extrusion behaviour of grits from flint and sweet corn. *Food Chemistry* 74: 303 – 308.

Hagenimana, A., Ding, X. and Fang, T. (2006). Evaluation of rice flour modified by extrusion cooking. *Journal of Cereal Science* 43: 38 – 46.

Harmann, D.V. and Harper, J.M. (1973). Effect of extruder geometry on torque and flow. *American Society of Agricultural Engineering* 16: 1175 – 1178.

Harper, J.M. (1981). *Extrusion of Foods*. Vol. II. CRC Press, Boca Raton, FI.

Harper, J.M. and Tribelhorn, R.E. (1992). Expansion of native cereal starch extrudates. In Kokini, J.L., Ho, C.T. and Karwe, M.V. *Food Extrusion Science and Technology*. Marcel Dekker, New York, pp. 653 – 667.

Hsieh, F., Mulvaney, S.J., Huff, H.E., Lue, S. and Brent, J. (1989). Effect of dietry fiber and screw speed on some extrusion processing and product variables. *LWT-Technology* 22: 204 – 207.

Hsieh, F., Peng, I.C., and Huff, H.E., (1990). Effects of salt, sugar and screw speed on processing and product variables of corn meal extruded with a twin-screw extruder. *J. Food Sci.* 55 (1): 224 – 227.

Hsieh, F, Grenus, K.M., Hu, L. and Huff, H.E. (1993). Twin-screw extrusion of rice flour with salt and sugar. *Cereal Chemistry* 70 (5): 493 – 498.

Hu, L., Hsieh, F. and Huff, H.E. (1993). Corn meal extrusion with emulsifier and soybean fiber. *Lebensmitted-Wissenschaft und Technologie* 26: 544 – 551.

Ilo, S., Liu, Y., and Berghofer, E. (1999). Extrusion cooking of rice flour and amaranth blends. *Lebensmittel-Wissenschaft und Technologie* 32: 79 – 88.

Janes, D.A. (1993). Methods for assessing raw materials and extrudates. *Ingredients Extra* 12: 93 9 – 34.

Jideani, V.A., Nkama, I., Agbo E.B. and Jideani, I.A. (2002). Identification of the hazard and critical control (HACCP) in traditional fura manufacture. *Nigerian Food Journal* 19: 42 – 48.

Kirby, A.R., Ollet, A.L., Parker, R. and Smith, A.C. (1988). An experimental study of screw configuration effects in the twin-screw extrusion-cooking of maize grits. *Journal of Food Engineering* 8: 247 – 272.

Kokini, J.L., Chang, C.N., and Lai, L.S. (1991). The role of rheological properties on extrudate expansion. In Kokini, J.K., Ho, C.T. and Karwe, M.V. (eds.), F*ood extrusion Science and Technology*. Marcel Dekker, New York, pp. 345 – 360.

Launary, B. and Lisch, J.M. (1983). Twin-screw extrusion cooking of starches: Flow behaviour of starch pastes, expansion and mechanical properties of extrudates. *Journal of Food Engineering* 2: 259 – 280.

Likimani, T.A., Sofos, J.N., Maga J.A. and Harper, J.M. (1991). Extrusion cooking of corn/soybean mix is presence of thermostable a-amylase. *J. Food Sci.* 56: (1) 99 – 105.

Lu, Q., Hsieh, F., Mulvaney, S.J., Tan, J., and Huff, H.E. (1992). Dynamic analysis of process variables for a twin screw extruder. *Lebensmittel-Wissenshaft U-Technologie* 25 (3): 261 – 270.

Mange, C. and Boissonant, P. (1987). Distribution of residence time and comparison of three twin screw extrusion of different size. In O' Connor, C. (ed.) *Extrusion Technology for the Food Industry*. Elsevier Applied Science, London, pp. 117 – 131.

Martelli, F. G. (1983). *Twin Screw Extuders: A Basic understanding*. Van Nostrand Rheinhold Company, New York.

Meng, X., Threinen, D., Hansen, M. and Driedger, D. (2010). Effects of extrusion conditions on system parameters and physical properties of a chickpea flour-based snack. *Food Research International* 43: 650 – 658.

Meuser, F. and van Lengerich, B. (1984a). System analytical model for the extrusion for the extrusion of starches. In: *Thermal Processing and Quality Control of Foods*, eds P.

Meuser, F., van Lengerich, B., Pfaller, W. and Harmuth – Hoene, A.E. (1985). The influence of HTST extrusion cooking on the protein nutritive value of cereal based products, AACC 70th Annual Meeting, Orlando, Florida.

Meuser, F., Pfaller, W. and van Lengerichi, B. (1987). Technological aspects regarding specific changes to the characteristic properties of extrudates by HTST extrusion cooking. In O' Connor C. (ed.) *Extrusion Technology for the Food Industry*. Elsevier Applied Science, London, pp. 35 – 53.

Mohammed, S. (1990). Factors affecting extrusion characteristic of expanded starch-based product. *J. Fd. Proc. and Preser.* 14: 437 – 452.

Moore, G. (1994). Snack food extrusion. In Frame, N.D. (ed.). *The Technology of Extrusion Cooking*. Blackie Academic and Professional, an imprint of Chapman and Hall, Bishopbriggs, Glassgow.

Moraru, C.I. and Kokini, J.L. (2003). Nucleation and expansion during extrusion and microwave heating of cereal foods. *Comprehensive Reviews in Food Science and Food Safety*. 2 (4): 120 –138.

Padmanabhan, M. and Bhattacharya, M. (1989). Analysis of pressure drop in the extruder dies. *J. Food Sci.* 54 (3): 709 – 713.

Qing-Bo, D., Ainsworth, P., Tuker, G. and Marson, H. (2005). The effect of extrusion conditions on the physicochemical properties and sensory characteristics of rice-based expanded snacks. *Journal of Food Engineering* 66: 284 – 289.

Ryu, G.H., and Ng, P.K.W. (2001). Effects of selected process parameters on expansion and mechanical properties of wheat flour and whole cornmeal extrudates. *Starch/Starke* 53: 147 – 154.

Seker, M. (2005). Selected properties of native starch or modified maize starch/soy protein mixtures extruded at varying screw speed. *J. of the Sc. of Food and Agric.* 85 (7): 1161–1165.

Senouci, A. and Smith, A.C. (1986). The extrusion cooking of potato starch material. *Starch/Strake* 38: 78 – 82.

Shukula, T. (1991). The dimensions of food extrusion research and technology. *Cereal Foods World* 36 7: 581 – 582.

Sin, H.N., Yusof, S., Abdul Hamid, N.S. and Rahman, R.A. (2006). Optimization of hot water extraction for sapodilla juice using response surface methodology. *Journal of Food Engineering* 74: 352 – 358.

Singh, N. and Smith, A.C. (1997). A comparative of wheat starch, whole-wheat meal and oat flour in the extrusion process. *Journal of Food Engineering* 34: 15 – 32.

Singh N., Smith, A.C. and Frame, N.D. (1998). Effect of process variables and monoglycerides on extrusion of maize Grits using two sizes of Extruder. *Journal Food Engineering* 35: 91 – 109.

Singh, S., Gamlath, S. and Wakeling, L. (2007). Nutritional aspects of food extrusion: A review. *International Journal of Food Science & Technology* 42: 916 – 929.

Sopade, P.A. and Le Grys, G.A. (1991). Effect of added sucrose on extrusion cooking of maize Starch. *Food Control* 20: 103 – 109.

SPSS Release 11, Standard Version, SPSS Inc., 1998.

Su, C.W. and Kong, M.S. (2007). Effects of soybean oil, cellulose, and SiO2 addition on the lubrication and product properties of rice extrusion. *Journal of Food Engineering* 78: 723 – 729.

Taranto, M.V. Cegla, G.F., Bell, R.K. and Rhee, K.C. (1978). Morphological, ultrastructural and rheological evaluation of soy and cottonseed flours texturized by extrusion and nonextrusion processing. *J. Food Sci.* 43: 973.

Wanasundara, P. K. J. P. D. and Shahidi, F. (1996). Optimization of hexametaphosphate-assisted extraction of flaxseed protein using response surface methodology. *J. Food Sci.* 61 (3): 604 – 607.

White, G. (1994). Defining the true meaning of snacks. *Food Technology International Europe* 2: 115 – 117.

Yeu, K., Lee. Y. and Lee., S.Y. (2008). Consumer acceptance of an extruded soy-based high-protein breakfast cereal. *J. Food Sci.* 73 (1): S20 – S25.

Yuliani, S., Torley, P.J., D'Arcy, B., Nicholson, T. and Bhandari, B. (2006). Extrusion of mixtures of starch and D-limonene encapsulated with β-cyclodextrin: Flavour retention and physical properties. *Food Research International* 39: 318 – 331.

Zasypkin, D.V. and Tung-Ching, L. (1998). Extrusion of soybean and wheat flour as affected by moisture content. *J. Food Sci.* 63 (6): 1058 – 1061.