International Food Research Journal 21(6): 2399-2304 (2014)
Journal homepage: *http://www.ifrj.upm.edu.my*

The optimization of extrusion condition of Phatthalung Sungyod rice extrudate: a preliminary study

[1*]Keawpeng, I., [2]Charunuch, C., [3]Roudaut, G. and [4]Meenune, M.

[1]*Faculty of Agricultural Technology, Songkhla Rajabhat University, Muang, Songkhla 90000, Thailand*
[2]*Institute of Food Research and Product Development (IFRPD), Kasetsart University, Bangkok 10900, Thailand*
[3]*Department of Molecular and Sensory Engineering of Foods and Pharmaceuticals – ENSBANA 1, Esplanade Erasme. F 21000 Dijon, France*
[4]*Faculty of Agro-Industry, Prince of Songkla University, Hat-Yai, Songkhla, 90112 Thailand*

Article history

Received: 13 January 2014
Received in revised form: 13 May 2014
Accepted: 18 May 2014

Keywords

Extrusion cooking
Brown rice
Physicochemical properties
Optimization
Response surface methodology

Abstract

Phatthalung Sungyod rice flour was supplied to extrude in a co-rotating twin screw extruder. The effects of extrusion conditions such as, barrel temperature (135-165°C), screw speed (300-400 rpm) and feed moisture contents (12.5-17.5%) on physicochemical properties of rice extrudate and the optimized condition were studied by the use of response surface methodology (RSM). The second-order polynomials were used to model the product response as a function of process variables and the multiple regression equations were obtained to describe effect of each variable on product responses. Barrel temperature, screw speed and feed moisture content had significant effects on density, expansion ratio, water absorption index (WAI), water solubility index (WSI) and hardness of rice extrudate. They were most affected by the changes in the level of feed moisture content and barrel temperature. At low feed moisture content and high temperature, rice extrudate appeared to be expanded with low density and more crispness. WAI and WSI of extrudate increased with increase barrel temperature and decrease feed moisture content. The hardness of rice extrudate varied between 23.31 and 54.24 N. At the highest feed moisture content, the lowest barrel temperature and screw speed, the highest value of product's hardness was obtained. The optimized extrusion condition for produced rice extrudate was at low feed moisture (12.5%), low screw speed (300 rpm) and high barrel temperature (165°C). With this condition, the well expansion, low product density and more crispness of extruded snack were obtained.

Introduction

Snacks are widely consumed as convenience food products. They can be produced using a wide variety of processing techniques among which is extrusion cooking. Extrusion cooking has become one of the most popular technologies in food processing. It is a low cost, high temperature short time (HTST) process, use worldwide for processing of a number of food products (Singh *et al.*, 2007a). It is a powerful processing operation, which utilizes high temperature, pressure, and shear force to produce highly expanded, low-density products with unique texture properties. Extrusion of snack foods demands close control of many variables such as feed moisture, feed composition, feed particle size, feed rate, barrel temperature, screw speed, screw configuration, and die geometry. These process variables determine the extent of macromolecular transformations during extrusion, which in turn influence the rheological properties of the food melt in the extruder and the physical characteristics of extrudates. Consequently, changing the factors can influence extrusion behavior and the quality of extruded products (Frame, 1994; Reyes-Moreno *et al.*, 2003; Singh *et al.*, 2007b). Physical characteristics such as expansion, density, and hardness are important parameters to evaluate the consumer acceptability of the final product (Patil *et al.*, 2007).

To produce the puff extruded snack, starch is the main constituent and is responsible for most of their structural attributes. Most raw materials have been used to develop various types of snack foods. The basic component of investigation is starch from corn, wheat, rice and potato, which is the key component for the product structuring and foaming (Bhattacharya *et al.*, 1986; Bhattacharya, 1997; Matthey and Hanna, 1997; Sun and Muthukumarappan, 2002; Fernandez-Gutierrez *et al.*, 2004; Singh *et al.*, 2007a; Anton *et al.*, 2009). Among these, rice has some special properties and it can widely use in the food industry due to the search for new sources of starches with special properties to improve the quality of products and processes. It has excellent expansion properties

*Corresponding author.
Email: *ittiporn_k@yahoo.com*
Tel: +66 7433 6964; Fax: +66 7433 6964

because of its high starch content and is well suited to thermal extrusion process.

In southern Thailand, there are much more than 4,000 varieties of the traditional rice Phatthalung Sungyod rice is a rice variety which most produce in Songkhla Lake Basin, covering three provinces, Nakhon Si Thammarat, Songkhla and Phatthalung. Phatthalung Sungyod rice is a pigmented rice, which it contain a natural colorant, called anthocyanin. A commonly found anthocyanin in red rice is acetylated procyanidins, which is reported to possess a free radical scavenging activity. The contents of GABA (γ-aminobutyric acid), γ-Oryzanol and Ferulic acid were found in Phatthalung Sungyod rice, as reported by Banchuen *et al.* (2010).

According to the extrusion conditions and feed composition affect structural and textural characteristics of extruded snacks. Recently, there are several studies investigating the effect of extrusion conditions on structural and textural characteristics of starch-based extrudates (Onwulata *et al*., 2001; Fernandez-Gutierrez *et al.*, 2004; Ding *et al*., 2006; Chaiyakul *et al*., 2009; Meng *et al.*, 2010). Therefore, the objective of this study was to evaluate the optimized extrusion condition for producing extrudate from Phatthalung Sungyod rice. The changes in physicochemical properties of rice extrudate (expansion ratio, density, WAI, WSI and hardness), as resulted from extrusion conditions (barrel temperature, screw speed and feed moisture) were reported and described by response surface methodology.

Materials and Methods

Sample preparation

Rice grain was obtained from Phatthalung province, southern Thailand. It was harvested in 2013. After harvested, rice were dried as a commercial method, dehulled and processed to obtain rice flour. The particle size of rice flour was range between 40-60 mesh and its moisture content was 11.27% (db.) according to the method of AOAC (2000).

Extrusion cooking

The extrusion trials were performed with an intermeshing co-rotating twin screw extruder (Hermann Berstorff Laboratory, The Twin Screw Extruder ZE 25 x 33D). This extruder comprises of 7 parts of barrel, end with a 24.5 mm thick die plate with one slit (1 mm × 20 mm) and the barrel length to diameter ratio (L/D) of the extruder is 870:25. This screw profile is made up of conveying self-wiping elements except for a section consisting of short reverse at the end of barrel. The material was fed into the extruder using a volumetric twin screw feeder (K-Tron soder AG 5702, type 20, Switerland). Barrel temperature (135, 150 and 165°C), screw speed (300, 350 and 400 rpm) and feed moisture (12.5, 15 and 17.5%) were varied, the extrusion conditions are shown on Table 1. After the steady-state conditions, the extrusion response parameters die temperature and die pressure were constant, extrudates were collected and suddenly dried in hot air oven for 5 min, then packed in Nylon/LLDPE plastic bags and stored at room temperature until analyze for further properties.

Bulk density

The apparent density was determined by measuring the actual dimensions of the extrudates. The diameter of extrudates was measured with a Vernier caliper (Mitutoyo, Tokyo, Japan). The apparent density of extrudates was determined using the equation:

$$\rho_{app} = \frac{4 \times m}{\pi \times d^2 \times L}$$

where m is the mass of the samples (g), d is the diameter (cm) and L is the length of extrudate (cm). The results are the average of 10 replicate measurements.

Expansion ratio

To determine the expansion ratio (ER), the cross-sectional diameter of the extrudates was measured with a Vernier caliper (Mitutoyo, Tokyo, Japan). The expansion ratio was calculated as the cross-sectional diameter of the extrudate divided by the diameter of the die opening (Ding *et al*., 2005; Onwulata *et al.*, 2001). It was obtained from 10 random samples for each extrusion condition.

Water absorption (WAI) and water solubility index (WSI)

The WAI and WSI were measured as a method of Anderson *et al.* (1969). The extrudates were ground and 2.5 g of sample was suspended in 25 ml of distilled water, the glass rod was used to break up any lumps. After stirring for 30 min, the dispersion was rinsed into a centrifuge tube and centrifuged at 5000 rpm for 10 min. The supernatant was decanted for determination of its solids content and the sediment was weighed. WAI was calculated using the equation:

$$\text{WAI}(\text{g/g, db}) = \frac{\text{Weight of gel (g)}}{\text{Weight of ground dry sample (g)}}$$

The supernatant liquid from the WAI determination was dried at 105°C until constant weight was reached. The amount of dried solid recovered from evaporating the supernatant was expressed as a percentage of dry solids in the 2.5 g ground dry sample and defined as water solubility index (WSI).

$$\text{WSI (\%)} = \frac{\text{Dry solid (g)}}{\text{Weight of ground dry sample (g)}} \times 100$$

Hardness

The hardness of samples was measured using Stable Microsystems TA-XT2i Texture Analyzer (Texture Technologies Corp., Scarsdale, NY, USA). It was fitted with a 50 kg load cell. Samples were prepared and packed into a Kramer shear cell. The Kramer probe (5 blades, 3 mm thick, 64 mm high, 82 mm wide, 11 mm apart) was set to move at a test speed of 2.0 mm/s for a distance of 50 mm. The maximum force needed to break the samples was recorded.

Experimental design and statistical analysis

In this study, the response surface methodology (RSM) was used to investigate the optimized and the effect of extrusion conditions on the product responses of rice-based snack. The actual level ranges were selected according to the preliminary trial and literatures for suitable extrusion cooking. The outline of experimental design with the actual levels is presented in Table 1. The independent variables considered for this study were barrel temperature of the last zone (135–165°C), screw speed (300–400 rpm) and feed moisture content (12.5–17.5%). Face Centered Central Composite Design was employed to determine the extrusion conditions (Myers, 1971). Experiments were randomized in order to minimize the systematic bias in the observed responses due to extraneous factors.

Product responses (bulk density, expansion ratio, water absorption index (WAI), water solubility index (WSI) and hardness) were obtained as results of the proposed experimental design were subjected to regression analysis in order to assess the effects of feed moisture content, screw speed, and barrel temperature. A polynomial regression model

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_{12} X_1 X_2 + \beta_{13} X_1 X_3 + \beta_{23} X_2 X_3 + \beta_{11} X_1^2 + \beta_{22} X_2^2 + \beta_{33} X_3^2$$

The dependent variables were established to fit the experimental data for each response and computed by using Design expert (version 7.0), where X_i, $X_i X_i$, and XiXj are linear, quadratic, and interaction effect of the input variables which influence the response (Y), respectively. β_0, β_i, and β_{ij} are the regression coefficients to be determined. The response surface plots for these models were plotted as a function of two variables.

Results and Discussion

The effects of extrusion conditions, such as, barrel temperature, screw speed and feed moisture content on physicochemical properties of rice extrudates were studied. The difference in operation conditions of extruder has profound affected on properties of rice extrudates. The regression models of physicochemical properties of rice extrudate, such as, density, expansion ratio, WAI, WSI and hardness were significant ($P < 0.05$), with a high coefficient for determination (R^2 = 0.98, 0.96, 0.96, 0.99 and 0.68, respectively). All of model showed the non-significant lack of fit ($P > 0.05$).

Bulk density

Bulk density was significantly affected by the quadratic ($P < 0.05$) effects of feed moisture content and barrel temperature. The response surface plots of product density are showed in Figure 1. The product bulk density increased with increase in feed moisture, whereas decreased with increase in screw speed and barrel temperature. The density of extrudates varied between 0.35 and 0.64 g/cm^3. A similar result was observed in the study of Meng *et al*. (2010). They reported that the low density, a desirable characteristic of a chickpea flour-based expanded products, was obtained at low feed moisture, high screw speed and barrel temperature. The bulk density of extrudate also describes the degree of expansion undergone by the melt as it exits the extruder. The bulk density is used as a measurement of volumetric expansion which it would has less variability than the other types of expansion (Dogan and Karwe, 2003; Meng *et al*., 2010).

Expansion ratio

Expansion ratio is a measurement of expansion in diameter of extrudate. According to extrusion conditions were used in this study, the expansion ratio of extrudates was in the between 2.19 and 4.01. The results from regression analysis showed a significant ($P < 0.05$) effect of feed moisture content and barrel temperature on expansion of extrudates as main effect whereas there was a non-significant ($P > 0.05$) effect of screw speed on expansion. Feed moisture content has a significant negative quadratic effect, while barrel temperature and screw speed have a significant positive quadratic effect ($P < 0.05$) on the expansion of rice extrudates. It was observed from the response surface plot (Figure 2) that products showed a high in

Table 1. Experimental design for extrusion experiments

Run No.	Coded levels			Actual levels		
	X1	X2	X3	Barrel temperature (°C)	Screw speed (rpm)	Feed moisture content (%)
1	-1	-1	-1	135	300	12.5
2	-1	0	0	135	350	15.0
3	-1	1	-1	135	400	12.5
4	-1	1	1	135	400	17.5
5	-1	-1	1	135	300	17.5
6	0	1	0	150	400	15.0
7	0	0	1	150	350	17.5
8	0	-1	0	150	300	15.0
9	0	0	0	150	350	15.0
10	0	0	0	150	350	15.0
11	0	0	-1	150	350	12.5
12	1	0	0	165	350	15.0
13	1	-1	-1	165	300	12.5
14	1	1	1	165	400	17.5
15	1	-1	1	165	300	17.5
16	1	1	-1	165	400	12.5

Table 2. The regression parameter coefficient product properties using independent variables barrel temperature (X1), screw speed (X2) and feed moisture content (X3) of Phatthalung Sungyod rice extrudates

Parameters	Regression parameter coefficients of product responses				
	Density (g/cm^3)	Expansion ratio	WAI (g/g, db)	WSI (%, db)	Hardness (N)
Intercept	0.4095	3.6876	5.2034	40.8038	28.4609
Barrel temperature (X1)	-0.0190	0.0850	0.0540	0.3780	-1.3850
Screw speed (X2)	-0.0070	0.0040	-0.1130	-1.5170	0.7850
Feed moisture (X3)	0.1520	-0.5730	-0.6420	-14.5040	14.2700
Barrel temperature × Screw speed (X1×X2)	0.0063	-0.0100	0.0150	0.0387	0.1463
Barrel temperature × Feed moisture (X1×X3)	-0.0013	0.0700	-0.0025	0.0212	0.2988
Screw speed × Feed moisture (X2×X3)	-0.0038	0.0475	0.0575	0.0037	-0.9288
Barrel temperature × Barrel temperature ($X1^2$)	-0.0317	0.1236	-0.1252	0.0693	-0.0138
Screw speed × Screw speed ($X2^2$)	0.0283	-0.1714	0.1398	1.1543	0.2362
Feed moisture × Feed moisture ($X3^2$)	0.0333	-0.6164	-0.3252	-4.9007	9.3412
P-value for model	<0.001	0.001	0.001	<0.001	<0.001
R^2	0.98	0.96	0.96	0.99	0.68
P-value for lack of fit	0.21	0.08	0.26	0.54	0.78

expansion ratio at low level of feed moisture content. However, a small increase in expansion ratio was observed with the increase in barrel temperature and screw speed. This was in agreement with the study of Ding *et al.* (2005) and Ding *et al.* (2006). They reported that the extrudate expansion was found to be most dependent on feed moisture. Increased feed moisture leads to a sharp decrease in the expansion of extrudate. However, screw speed and barrel temperature also have significant effects on their expansion. A small increase in expansion ratio was noticed with the increase in barrel temperature and screw speed.

Water absorption (WAI) and water solubility indices (WSI)

WAI of extrudates ranged from 4.18 to 5.68 g/g dry sample. The significant negative coefficient (P < 0.05) of the linear terms of feed moisture and screw speed level indicated that WAI decreased with increase in these variables while positive coefficient of the linear terms of barrel temperature resulted increase in WAI (P > 0.05). The WAI measures the volume occupied by the granule or starch polymer after swelling in excess water. While the WSI determines the amount of free polysaccharide or polysaccharide released from the granule after addition of excess water (Sriburi and Hill, 2000; Altan *et al.*, 2008). Similar results were reported by

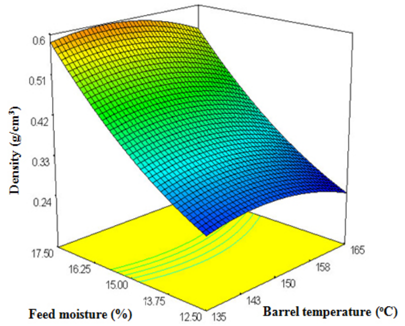

Figure 1. Effect of barrel temperature and feed moisture content on product density.

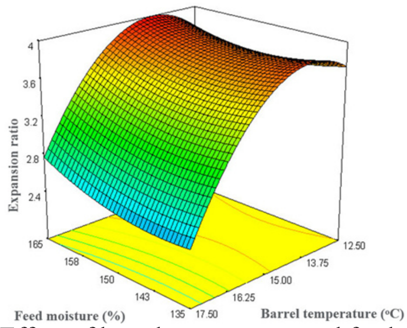

Figure 2. Effect of barrel temperature and feed moisture content on product expansion ratio.

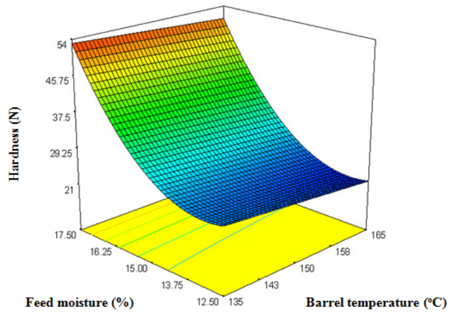

Figure 3. Effect of barrel temperature and feed moisture content on product hardness.

Bhattacharya (1997), Ding *et al.* (2006) and Altan *et al.* (2008). They reported that the significantly decrease in WAI of extrudate as the increase in barrel temperature. A decrease in WAI with increase in temperature was probably due to decomposition or degradation of starch. The WAI decreases with increasing temperature if dextrinization or starch melting prevails over the gelatinization phenomenon (Ding *et al.*, 2006). The WSI of extrudate ranged between 20.25 and 53.43% (db). It increased with increase in barrel temperature (P > 0.05), whereas negative coefficient effects (P < 0.05) of feed moisture and screw speed were observed. Gujska and Khan (1990) reported a significant increase in WSI with increase in extrusion temperature for the high starch fraction of different beans. Increase in WSI, with decrease in moisture content, may be attributed to higher degradation of starch (Anderson *et al.*, 1969). Similar effects of decrease in feed moisture on WSI have been previously reported for starch, maize grits, rice and wheat (Singh and Smith, 1997; Kirby *et al.*, 1988; Bryant *et al.*, 2001).

Hardness

Hardness of extrudates was significantly affected by quadratic effects of barrel temperature, screw speed and feed moisture content variables. Feed moisture content and screw speed had also significant positive effect ($P < 0.05$) on extrudate hardness, while barrel temperature had negative effect on hardness of extrudate products. The results are shown in Table 2. The response surface plots (Figure 3) showed that hardness decreased with decreasing feed moisture content and screw speed, whereas, with increasing barrel temperature, the hardness decreased. A positive correlation between bulk density and hardness has been reported by many researchers suggesting that a low density product naturally offers low hardness (Bhattacharya, 1997; Ding *et al*., 2006; Altan *et al.*, 2008; Meng *et al*., 2010). The hardness of extrudates ranged from 20.13 to 54.24 N. The low hardness is a favour property of extrudates. It was observed at low feed moisture, screw speed and high barrel temperature. The hardness of expanded extrudates is a perception of the human being and is associated with expansion and cell structure of the product. The hardness is the peak force required for a probe or parallel blades to penetrate the extrudate (Meng *et al*., 2010). The higher the value of maximum peak force required, which means the more force required to breakdown the sample, the higher the hardness of the sample to fracture (Altan *et al*., 2008). Similar result was reported by Chaiyakul *et al.* (2009). They reported that feed moisture and barrel temperature have a significant effect on the hardness of high protein glutinous rice-based extrudate. Increasing feed moisture content increased the breaking strength index of the extrudate. In contrast, increasing temperature, the breaking strength index of extrudate decreased. The decrease in hardness with increasing barrel temperature is in line with the results of bulk density reduction, whereas, the expansion of extrudate increased. Several studies reported the high correlation between bulk density and hardness that low density product naturally offers low hardness (Bhattacharya, 1997; Ding *et al.*, 2006; Altan *et al*., 2008; Meng *et al*., 2010). The effect of screw speed on hardness might be through its influence on extrudate expansion. The decrease in hardness with increasing screw speed was also observed in corn- and barley-based extrudates (Liu *et al*., 2000; Altan *et al.*, 2008). The increase in screw speed expected to lower the melt viscosity of the mix resulting in a less dense, softer extrudate (Ding *et al.*, 2006).

Conclusions

Change of extrusion conditions, especially, feed moisture, barrel temperature and screw speed affected the physicochemical properties of rice extrudate. The high expansion ratio and low bulk density were observed at high barrel temperature, high screw speed and low feed moisture. Increased feed moisture and screw speed increased in hardness of extrudate, while increased in barrel temperature hardness of product was decreased. Feed moisture and screw speed have negative effects on WAI and WSI, whereas barrel temperature has positive effect. The products with high expansion ratio and low product density, which generally are good characteristics of extruded snack, were produced at medium extrusion temperature, high screw speed, and low feed moisture.

Acknowledgments

The authors are grateful to The Program of Strategic Scholarships for Frontier Research Network for the Thai Doctoral degree Program (CHE510330); and the Office of the Higher Education Commission, Thailand for the financial support. We also thank the Institute of Food Research and Development (IFRPD), Kasetsart University, for extruder and technical support.

References

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.

Anderson, R. A., Conway, H. F. M., Pfeiffer, V. F. and Griffin, E. J. 1969. Gelatinization of corn grits by roll and extrusion cooking. Cereal Science Today 14: 4-12.

Anton, A. A., Fulcher, R. G. and Arntfield, S. D. 2009. Physical and nutritional impact of fortification of corn starch-based extruded snacks with common bean (*Phaseolus vulgaris* L.) flour: effects of bean addition and extrusion cooking. Food Chemistry 113: 989-996.

A.O.A.C. 2000. Official Methods of Analysis 16th ed. Washington, DC: Association of Official Analytical Chemists.

Banchuen, J., Thammarutwasik, P., Ooraikul, B., Wuttijumnong, P. and Sirivongpaisal, P. 2010. Increasing the bio-active compounds contents by optimizing the germination conditions of southern Thai Brown Rice. Songklanakarin Journal of Science and Technology 32: 219-230.

Bhattacharya, S. 1997. Twin-screw extrusion of rice-green gram blend: extrusion and extrudate characteristics. Journal of Food Engineering 32: 83-99.

Brummer, B., Meuser, F., Van Lengerich, B. and Niemann, C. 2002. Expansion and functional properties of corn starch extrudates related to their molecular degradation, product temperature and water content. Starch 54: 9-15.

Bryant, R. J., Kadan, R. S., Champagne, E. T., Vinyard, B. T. and Boykin, D. 2001. Functional and digestive characteristics of extruded rice flour. Cereal Chemistry 78: 131-137.

Chaiyakul, S., Jangchud, K., Jangchud, 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.

Ding, Q. B., Ainswoth, P., Tucker, 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: 283-289.

Ding, Q. B., Ainsworth, P., Plunkett, A., Tucker, G. and Marson, H. 2006. The effect of extrusion conditions on the functional and physical properties of wheat-based expanded snacks. Journal of Food Engineering 73: 142-148.

Dogan, H. and Karwe, M. V. 2003. Physicochemical properties of quinoa extrudates. Food Science and Technology International 9: 101-114.

Fernandez-Gutierrez, J. A., Martin-Martinez, E. S., Martinez-Bustos, F. and Cruz-Orea, A. 2004. Physicochemical properties of casein-starch interaction obtained by extrusion process. Starch/Stärke 56: 190-198.

Frame, N. D. 1994. The Technology of Extrusion Cooking. London: Blakie Academic and Professional.

Gujska, E. and Khan, K. 1990. Effect of temperature on properties of extrudates from high starch fraction of navy, pinto and garbanzo beans. Journal of Food Science Technology 55: 466-469.

Harper, J. M. 1981. Extrusion of Food. Boca Raton: CRC Press.

Hashimoto, J. M., Nabeshima, E. H., Cintra, H. S., Dias, A. R. G., Bustos, F. M. and Chang, Y. K. 2002. Effect of processing conditions on some functional characteristics of extrusion-cooked cassava starch/wheat gluten blends. Journal of Science and Food Agriculture 82: 924-930.

Kirby, A. R., Ollett, 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.

Liu, Y., Hsieh, E., Heymann, H. and Huff, H. E. 2000. Effect of process conditions on the physical and sensory properties of extruded oat-corn puff. Journal of Food Science 65: 1253-1259.

Matthey, F. P. and Hanna, M. A. 1997. Physical and functional properties of twin-screw extruded whey protein concentrate-corn starch blends. LWT – Food Science and Technology 30: 359-366.

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.

Myers, R. H. 1971. Response Surface Methodology. Boston: Allyn & Bacon.

Njoki, P. and Faller, J. F. 2001. Development of an extrudated plantain/corn/soy weaning food. International Journal of Food Science and Technology 36: 415-423.

Onwulata, C. I., Smith, P. W., Konstance, R. P. and Holsinger, V. H. 2001. Incorporation of whey products in extruded corn, potato or rice snacks. Food Research International 34: 679-687.

Onyango, C., Henle, T., Ziems, A., Hofmann, T. and Bley, T. 2004. Effect of extrusion variables on fermented maize-finger millet blend in the production of uji. LWT – Food Science and Technology 37: 409- 415.

Patil, R. T., Berrios, J. D., Tang, J. and Swanson, B. G. 2007. Evaluation of methods for expansion properties of legume extrudates. Applied Engineering in Agriculture 23: 777-783.

Reyes-Moreno, C., Milan-Carrillo, J., Gutierrez-Dorado, R., Paredes-Lopez, O., Cuevas-Rodriguez, E. O. and Garzon-Tiznado, J. A. 2003. Instant flour from quality protein maize (*Zea mays* L.). Optimization of extrusion process. LWT – Food Science and Technology 36: 685-695.

Singh, N., Singh, B., Sandhu, K. S., Bawa, A. S. and Sekhon, K. S. 1996. Extrusion behaviour of wheat, rice and potato blends. Journal of Food Science Technology 31: 291-294.

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

Singh, B., Sekhon, K. S. and Singh, N. 2007a. Effects of moisture, temperature and level of pea grits on extrusion behavior and product characteristics of rice. Food Chemistry 100: 198-202.

Singh, S., Gamlath, S. and Wakeling, L. 2007b. Nutritional aspects of food extrusion: a review. International Journal of Food Science and Technology 42: 916-925.

Sun, Y. and Muthukumarappan, K. 2002. Changes in functionality of soy-based extrudates during single screw extrusion processing. International Journal of Food Properties 5: 379-389.

Thymi, S., Krokida, M. K., Pappa, A. and Maroulis, Z. B. 2005. Structural properties of extruded corn starch. Journal of Food Engineering 68: 519-526.