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Optimization of Roba1 bean extrusion conditions and extrudate properties using Response surface methodology and multi-response desirability function

Hedwig Natabirwa[a,b,*], Dorothy Nakimbugwe[a], Mercy Lungaho[c], & John H Muyonga[a]

[a]*School of Food Technology Nutrition & Bioengineering, Makerere University, P.O Box 7062, Kampala, Uganda*

[b]*National Agricultural Research Laboratories, National Agricultural Research Organization, P.O. Box 7065, Kampala, Uganda*

[c]*Center for International Tropical Agriculture, P.O. Box 6247, Kampala, Uganda*

[*]**Corresponding author:** *School of Food Technology Nutrition & Bioengineering, Makerere University, P.O Box 7062, Kampala, Uganda. E-mail: hedwignorh@yahoo.com*

Abstract

Effects of extruder die temperature, screw speed and ingredient feed moisture on Roba1 bean extrudate nutritional and physicochemical properties were evaluated by response surface methodology (RSM) and extrusion processing conditions optimized for optimal extrudate attributes by multi-response desirability function. Responses taken were protein content, protein digestibility, polyphenols, phytates, extrudate expansion, bulk density, water absorption and water solubility index, as well as texture.. Feed moisture, die temperature and screw speed significantly ($p <$ 0.05) influenced the physicochemical properties of Roba1 extrudates ($R^2 \geq 0.500$). Increase in feed moisture at low die temperatures resulted in decrease in extrudate expansion ratio (~3.96%) and water solubility (~10%). Increases in expansion, and reduction in bulk density and water absorption index due to increase in screw speed and die temperature were also observed. Predictive desirability optimization generated optimal attributes (expansion ratio, 2.59; bulk density, 1.32; protein digestibility, 81.58%; and hardness, 24.4 N) for snack with desirability index of 0.75. Information from this study can be useful for optimization of bean snack extrusion process and product in the food industry.

Key words: Extrusion, common beans, optimization, desirability function, physicochemical properties, RSM

1. INTRODUCTION

Common beans (*Phaseolus vulgaris L.*) are a nutritious food consumed as a staple by a large population throughout the world, especially in developing countries (Anderson *et al.*, 2016). Beans not only provide proteins, but are also rich in vitamins, minerals and fibre (Nyombaire, Siddiq, & Dolan, 2011), and average daily per capita consumption ranges between 0.01 and 0.18 kg/day (Blair, 2013). Recently, new common bean varieties enriched with iron and zinc through conventional breeding were developed with the aim of reducing micronutrient malnutrition among vulnerable populations. Among these is Roba1 containing about 66.7 and 27.6 µg/g of Fe and Zn, respectively (Natabirwa, Muyonga, Nakimbugwe, & Lungaho, 2018). Roba1 is a high-yielding and multiple disease-resistant haricot bean variety currently produced in Sub-Saharan African countries (Ethiopia, Tanzania and Uganda), with average yield of about 1.8 tons/ha (Mukankusi, Nkalubo, Katungi, et al, 2015).Biofortified and iron-rich beans in general ontain higher levels of iron (~70 - 96 ug/g) and zinc and (~26 - 35ug/g) than the conventional beans (Bouis & Welch, 2010). The use of biofortified beans as major ingredients in processed foods would help to improve the nutritional quality. Bean consumption however has generally remained relatively low due to the lengthy cooking time which translates into high fuel costs (Rocha-Guzman *et al*., 2008), and monotonous preparation techniques involved. Moreover, common beans have hardly been explored as raw material in the food industry, except canning and to some extent, flour production (Nyombaire et al., 2011; Pedrosa et al., 2015). Even though sprouting, soaking, fermentation and roasting have been explored for nutritional improvement, the processes are cumbersome and can only be used on small-scale (Nkundabombi, Nakimbugwe, & Muyonga, 2015; Rehman, Salariya, & Zafar, 2001; Rocha-Guzman et al., 2008).

Extrusion cooking, a high temperature-short time industrial processing technique, has been singled out as the most promising method which can transform food raw material into highly nutritious, palatable and quality food (Ghumman, Kaur, Singh, & Singh, 2016; Siddiq, Kelkar, Harte, Dolan, & Nyombaire, 2013). Extrusion produces a range of food products from cereals and legumes (including flours, snacks, breakfast cereal, etcetera) with distinctive characteristics (Anton, Fulcher, & Arntfield, 2009; Meng, Threinen, Hansen, & Driedger, 2010; Nyombaire *et al*., 2011). The technology offers high efficiency in terms of fuel cost and output, but it is affected by a range of factors including ingredient type and extrusion conditions which determine the properties of extrudates (Ghumman et al., 2016; Steel et al., 2012). Notably, any variations in parameters such as extruder barrel temperatures, ingredient moisture, specific mechanical energy and screw speed, affect process variables as well as product quality.

Reports have shown that mild extrusion conditions (high moisture content, low residence time, low temperature) improve the nutritional quality of beans, while high extrusion temperatures (>200 °C), low moisture contents (< 15%) and/or improper formulation (such as presence of high-reactive sugars) can adversely impair the nutritional quality (Berrios, Ascheri, & Losso, 2012; Siddiq et al., 2013). However, studies on effects of extrusion processing conditions on extrudate properties have majorly been undertaken on conventional beans, other legumes and cereals (Ghumman *et al.*, 2016; Korus, Gumul, & Czechowska, 2007; Nyombaire *et al.*, 2011; Rathod & Annapure, 2017; Siddiq *et al.*, 2013).

Response Surface methodology (RSM) and multi-response desirability function can be used for optimization of processing conditions through exploration of relationship between several processes and responses (Altan, McCarthy, & Maskan, 2008; Bezerra, Santelli, Oliveira, Villar, & Escaleira, 2008; Jain, Monika; Singh, Chetna; Gupta, Kushboo; Jain, 2014). The RSM approach is important in design, development and formulation of new products, as well as improvement of existing product design (Bezerra *et al*., 2008). With the desirability function approach, operating conditions that meet the criteria set for optimization and provide the best value of compromise for combined responses, are established (Vera Candioti, De Zan, Cámara, & Goicoechea, 2014). Various product quality characteristics can be optimized together. For the extrusion of biofortified beans to be successful, critical control of processing conditions and a precise study of the variations that occur in product properties are necessary. The objective of this study was to investigate the effects of feed moisture, screw speed and die temperature on physicochemical and nutritional properties of Roba1 bean extrudate and; to determine the best combination of extrusion processing parameters for a desirable snack extrudate.

2. MATERIALS AND METHODS

2.1 Experimental design

Roba1 bean extrudates were developed following a Box Behnken design with three independent variables including ingredient feed moisture, extruder die temperature, and screw speed. Levels of each variable were established basing on preliminary trials and works from previous authors (Anton *et al.*, 2009; Berrios *et al.*, 2012). The three levels of process variables were coded as -1, 0 and 1, making the total number of experiments equal to 15 by Box Behnken design. Coded and actual values for process variables are given in Table 1.

Table 1 Coded and actual values used in developing experimental data

Factors	Factor codes	Level codes and actual values		
		-1	0	1
Die temperature (°C)	X_1	120	135	150
Feed moisture (%)	X_2	15	17.5	20
Screw speed (Hz)	X_3	35	40	45

2.2 Material preparation

Newly harvested dry beans of variety Roba1, a plain cream coloured bean enriched with iron and zinc through biofortification, were purchased from farmers in Rakai district, Uganda. The beans were sorted, washed with clean tap water and solar dried at temperatures 30 – 55°C for approximately 20 hours. Dried bean grains were milled using a commercial mill (Model YZMF, Yize, Shuliy Henan, China), to pass through a 1.5 mm sieve.

2.3 Extrusion

Beans were extruded in a Twin Screw Extruder (Model DP 70-III, Jinan, China) at barrel temperatures 60/100/120°C, 60/110/135 °C and 60/110/150 °C, and feed moisture 15 to 20 % and screw speeds (35, 40 and 45 Hz), as described in Table 1 above. The die diameter, screw diameter and length to diameter ratio of extruder were 5 mm, 27 mm and 18:1, respectively. Resultant extrudates were cooled to room temperature, and milled using a Stainless Steel mill (Model 30B-C, Changzhou, China) to pass through a 1.5 mm pore size sieve.

2.4 Extrudate analysis

2.4.1 Physicochemical properties

Extrudate expansion ratio (*ER*) and bulk density (BD) were determined according to methods described (Natabirwa, Muyonga, Nakimbugwe, & Lungaho, 2017). Water absorption index (WAI) and water solubility index (WSI)were determined using methods described (Natabirwa *et al*., 2017; Nyombaire *et al*., 2011). The final pasting viscosity of extruded flour was determined using extrusion profile on a Rapid Viscoanalyzer, Model RVA 4500, (Perten Instruments, Australia) using methods described (Natabirwa *et al*., 2017).

2.4.2 Extrudate texture

The texture of cylindrical extrudates (approximately 3 – 4 cm long pieces) was measured using a Stable Microsystems Texture Analyzer (Model TA.XT-Plus 42095, UK) by compression with a cylindrical probe of 6 mm diameter (SMS P/6) following methods described (Altan *et al*., 2008) with modifications. Hardness in newtons (N) was determined by measuring the maximum force required to break the extruded samples (~ 40 mm long), while crunchiness was determined as the average area under the force-deformation curve. The test speed was 2mm/s and the penetration distance was 5mm, with a trigger force 0.049 N. Post-test speed was 10.00 mm/sec. The return distance of the probe was kept at 20 mm. A force time curve was recorded and analyzed by Texture Exponent 32 Software programme. Ten (10) measurements were performed on each sample and averaged.

2.4.3 Protein digestibility

A multi-enzyme in vitro technique (Hsu, Vavak, Satterlee, & Miller, 1977; Krupa-Kozak & Soral-Śmietana, 2010) was applied for determination of protein digestibility since it could avoid under-predicting the digestibility of proteins. The digestibility was calculated using the regression equation (eq. 1) (Hsu *et al*, 1977).

$$Protein\ digestibility\ (\%) = 201.464 - 18.103 \times H \qquad (1)$$

where, H is the pH value of the sample suspension after 10 minutes digestion with the multi-enzyme solution.

2.4.4 Total polyphenol content

Total polyphenol content was determined using the Folin-Ciocalteau reagent, as described (Makkar, 2000; Natukunda, Muyonga, & Mukisa, 2016), with modifications. Briefly, 0.20 g of finely ground bean flour was measured into a 50 ml polypropyrene tube and extracted twice using 5 ml of methanol:water (50:50, v/v) with ultrasonication (20 min). The extraction solution was centrifuged at 3000 x g, for 10 min.), and the supernatant (extract) was stored at 4°C in a refrigerator until time for use. Total polyphenols in the extract were then determined as described (Natukunda *et al*., 2016). A standard curve was prepared with gallic acid at concentrations 0.00, 0.02, 0.04, 0.06, 0.08 and 0.10 mg/ml. Final results were expressed as gallic acid equivalents (mg GAE/100 g of bean flour).

2.4.5 Phytate determination

Phytate content was determined according to the method described (Gao *et al*., 2007) with modifications. Briefly, 0.5 g of raw and extruded bean flour (ground to pass through a 1.0 mm screen) was weighed into clean 15 mL polypropyrene tubes, and 10 mL of 2.4% HCl extraction solution was added. The tubes were shaken at 220 rpm for 16 h in an Orbital Incubator/Shaker (Model, Stuart S1600C, Wagtech) and centrifuged at 1000 x g for 10 min. at 10 °C. The extract was collected into a new set of falcon tubes containing 1 g NaCl each. The contents were vortexed for approx. 1 min. to dissolve the salt and allowed to settle at 4 °C for 60 min. The mixtures were centrifuged again at 1000 x g for 10 minutes, and clear supernatants were collected for colour development. An aliquot of clear supernatant (1 mL) was diluted 25 times in a 50-mL polypropyrene tube with distilled deionized water. A portion (3 mL) of the diluted sample was combined with 1 mL of modified Wade reagent (0.03% $FeCl_3.6H_2O$ + 0.3% sulfosalicyclic acid) in a 15-mL falcon tube, thoroughly mixed on a vortex and absorbance of colour reaction determined at 500 nm using a UV spectrophotometer (UVLine 9400, Schott Instruments, France).

A standard curve was prepared using series of calibration standards containing 0, 1.12, 2.24, 3.36, 5.6, 7.84, or 11.2 mg L−1 PA-P from phytic acid sodium salt hydrate (Sigma, *P8810*) and phytic acid content determined as above.

2.5 Statistical analysis and process optimization

Means and standard deviations for experimental data were computed using Statistica 7.0 (Tulsa, OK, USA). Response surface methodology (RSM) was used to relate product characteristics to extrusion variables. Response surface plots were generated as a function of two variables, while keeping the third variable constant at its intermediate value. Regression coefficients were generated by a second order polynomial:

$$Y_i = B_o + B_i \sum_{i=1}^{3} X_i + B_{ii} \sum_{i=1}^{3} {X_i}^2 + B_{ij} \sum \sum_{i,j=1}^{3} X_i X_j + \varepsilon \qquad (2)$$

where, Y_i is a response variable;B_0 is a constant; B_i, B_{ij} are gradients; $X_{i,j}$ are factors; and ε is error term.

The simultaneous optimization of the process conditions and product responses (protein digestibility, WAI, WSI, extrudate expansion ratio (ER), bulk density and hardness) for Roba1 bean snack was accomplished using a multi-response desirability method (Derringer & Suich, 1980). Individual desirability functions for each response variable were manipulated to achieve optimum values (Granato, Ribeiro, Castro, & Masson, 2010). In this study, WAI, bulk density and extrudate hardness demanded minimization, while protein digestibility, WSI and ER were maximized.

3. RESULTS AND DISCUSSION

3.1 Extrudate physicochemical properties

Roba1 bean extrudate properties differed significantly with variation in die temperature, feed moisture and screw speed (Tables 2, 3 and 4). The coefficients of determinations (R^2) for regression equations varied between 0.484 and 0.842 with significant probability values ($p < 0.05$, $p < 0.01$ and $p < 0.001$) (Table 4). Significant negative quadratic effects ($p < 0.01$) of die temperature and positive interaction effects ($p < 0.05$) of die temperature with feed moisture on protein digestibility were observed (Table 4). Total polyphenols were significantly decreased with increase in feed moisture (linear terms, $p < 0.05$) and interactions of die temperature (linear) with feed moisture (quadratic). Increases in screw speed (linear terms) and feed moisture (quadratic terms) resulted in increases in total polyphenols. The increases in screw speed (quadratic) and interaction effects of die temperature (quadratic) with screw speed (linear) resulted in decrease in total polyphenols. Possibly high screw speed limits the time of exposure of polyphenols to heat destruction (Anton *et al*, 2008).

Phytates are considered undesirable in foods since they form complexes with major divalent and trivalent cations (Ca, Fe, Zn, Mg and Cu) bearing an effect on mineral uptake, and also bind with proteins affecting their nutritional quality and absorption (Greiner, R., Konietzny, U., Jany, 2006). In this study, reduction in phytate content (Table 3) by at least 12 % as a result of extrusion was observed. Raw Roba1 flour was initially analyzed with average phytate content of 38.3 mg/g. No significant effect of change in feed moisture, die temperature and/or screw speed (linear, quadratic or interaction terms) on phytates were observed ($p > 0.05$) for Roba1 extrudate as seen from regression models.

Table 2 Effect of extrusion conditions on Roba1 extrudate nutritional properties

Values represent means of three replicates ± standard deviations.

Exp. run	**Feed moisture (%)**	**Die Temp. (°C)**	**Screw speed (Hz)**	**Protein content (g/100g)**	**Protein digestibility (%)**	**Polyphenol content (mg/100g)**	**Phytate content (mg/g)**
1	15.0	120	40	23.49±0.01	82.33±0.48	27.86±3.12	28.89±1.39
2	17.5	120	35	24.04±0.34	82.89±0.52	23.72±4.92	28.52±1.34
3	17.5	120	45	24.04±0.07	82.16±0.90	24.15±1.65	30.41±1.70
4	20.0	120	40	24.88±0.78	80.59±1.80	23.15±0.53	25.89±2.65
5	15.0	135	35	22.26±1.37	83.40±0.10	22.72±0.87	27.99±2.11
6	15.0	135	45	24.29±0.41	81.44±0.55	31.22±1.11	31.02±3.48
7	17.5	135	40	24.05±0.05	83.64±0.43	24.34±4.20	30.49±1.83
8	20.0	135	35	24.00±0.13	82.64±0.76	17.91±2.66	29.15±0.41
9	20.0	135	45	24.10±0.04	82.34±0.77	20.20±1.64	32.12±3.46
19	15.0	150	40	24.16±0.49	82.41±1.26	30.73±0.55	26.38±4.47
11	17.5	150	35	23.59±0.08	81.08±0.30	24.53±4.42	33.58±3.24
12	17.5	150	45	24.72±0.40	81.59±0.71	18.58±2.12	29.48±0.16
13	20.0	150	40	24.22±0.31	82.40±0.14	35.71±1.73	33.01±1.87

Table 3 Mean values of extrudate physical and functional properties

Exp. run	**Feed moisture (%)**	**Die Temp. (°C)**	**Screw speed (rpm)**	**WAI (g / g)**	**WSI (mL/g)**	**Radial expansion ratio (ER)**	**Bulk density (g/cm^3)**	**Peak force (N)**	**[Area F-D (cm)$^{2\,*}$**	**Mean force (N)**	**Final viscosity[1] (cP)**
1	15.0	120	40	3.98±0.61	0.39±0.06	2.52±0.07	1.50±0.06	30.22±1.48	123.72±4.93	16.50±0.68	259.00±22.00
2	17.5	120	35	4.67±0.10	0.33±0.02	2.45±0.07	2.06±0.05	46.17±5.71	158.58±10.62	21.82±0.65	323.67±7.38
3	17.5	120	45	4.35±0.35	0.36±0.02	2.50±0.01	1.81±0.08	34.08±1.63	132.64±5.79	17.49±1.07	307.20±16.80
4	20.0	120	40	4.20±0.18	0.35±0.05	2.40±0.03	2.17±0.33	48.20±1.28	172.82±8.74	23.29±1.21	333.50±24.10
5	15.0	135	35	3.69±0.29	0.41±0.03	2.52±0.05	1.49±0.25	32.66±1.84	130.85±5.35	17.47±0.74	302.70±10.90
6	15.0	135	45	3.47±0.08	0.46±0.00	2.59±0.07	1.33±0.05	25.62±1.15	110.14±3.72	14.71±0.50	298.80±23.70
7	17.5	135	40	3.98±0.30	0.38±0.02	2.45±0.06	1.84±0.04	35.65±3.67	140.31±9.36	18.72±1.25	286.94±9.27
8	20.0	135	35	4.43±0.17	0.36±0.02	2.36±0.04	1.85±0.58	35.17±4.85	137.35±13.76	18.33±1.84	335.80±14.70
9	20.0	135	45	3.86±0.49	0.38±0.01	2.47±0.05	1.78±0.01	29.50±3.43	120.66±8.90	16.34±1.31	292.00±9.02
19	15.0	150	40	3.63±0.27	0.36±0.10	2.54±0.04	1.58±0.31	26.38±4.79	112.90±13.79	15.08±1.84	298.00±33.40
11	17.5	150	35	4.47±0.13	0.36±0.01	2.42±0.01	2.15±0.05	43.10±3.33	159.03±8.39	21.23±1.14	320.50±45.90
12	17.5	150	45	3.97±0.08	0.42±0.01	2.48±0.03	1.63±0.04	29.78±0.58	122.17±2.70	16.31±0.38	278.70±28.40
13	20.0	150	40	3.71±0.30	0.42±0.03	2.53±0.01	1.72±0.07	31.86±2.86	131.40±20.09	17.54±2.70	308.80±19.50

Values represent means of three replicates ± standard deviations

[1] *Final pasting viscosity determined at 95°C using RVA*

* *Area F-D, Area of force deformation curve, (cm)^2*

Table 4 Regression coefficients of the linear, quadratic and interaction effect of feed moisture die temperature and screw speed on Roba1 extrudate properties

Variable	Protein digestibility	Total polyphenols	WAI	WSI	Radial expansion ratio	Bulk density	Hardness (Peak Force)	Area F-D	Mean force
Constant	**83.640*****	**24. 823*****	**3.983*****	**0.384*****	**-2.451*****	**1.837*****	**35.647*****	**140.310*****	**18.723*****
Die temperature (X_1)	-0.597	-1.171	-0.060	**0.022***	-0.011	-0.024	-1.844	-2.505	0.442
Feed moisture (X_2)	0.038	**-3.623****	**0.283****	**-0.031****	**-0.069*****	**0.204****	1.600	4.256	-0.623
Screw speed (X_3)	-0.566	**3.032****	**-0.198***	0.003	**0.042****	-0.120	**-3.179***	**-9.348****	**-1.186***
X_1*X_1	**-1.117****	1.979	0.147	-0.019	-0.001	0.054	**3.033***	**6.628***	0.381
X_2*X_2	-0.589	**2.561***	**-0.257****	0.014	**0.035***	**-0.197****	**-4.512****	**-11.728*****	**-0.939***
X_3*X_3	-0.597	**-4.038*****	0.136	0.003	0.013	-0.029	-0.398	-3.834	**-1.559*****
X_1*X_2	0.432	2.425*	**-0.195***	**0.023***	0.029	**-0.131***	**-3.125****	**-7.651***	**-1.083****
X_1*(X_2^2)	**1.070***	**-5.028****	-0.142	-0.013	**0.049***	-0.070	**-3.201***	**-10.552***	**-1.350***
(X_1^2)*X_2	-0.474	**3.691***	-0.048	**0.035***	0.009	-0.001	**4.264****	**12.644****	**1.689****
X_1 X_3	0.308	-1.578	0.004	0.005	0.004	-0.069	-0.306	-2.731	-0.147
(X_1^2)*X_3	0.513	**-4.396***	-0.072	0.003	0.012	-0.138	**-3.172***	-6.352	**-1.127***
X_2*X_3	0.415	-1.219	-0.085	-0.001	-0.013	0.024	0.342	1.005	0.190
R^2	*0.484*	*0.653*	*0.651*	*0.499*	*0.645*	*0.659*	*0.842*	*0.803*	*0.817*

* Significant at $p < 0.05$

** Significant at $p < 0.01$

*** Significant at $p < 0.001$

Extrudate expansion and bulk density

Increases in feed moisture by linear terms resulted in reduced expansion of Roba1 extrudate, while increases in screw speed (linear), feed moisture (quadratic) and interaction terms of die temperature with feed moisture resulted in increased extrudate expansion (Table 4). Decreases in expansion at high feed moisture might be due to reduced elasticity of dough through plasticization of melt in the extruder (Ding, Ainsworth, Plunkett, Tucker, & Marson, 2006; Hagenimana, Ding, & Fang, 2006). The significant increases in expansion ($p < 0.01$) due to increased screw speed may be attributed to bubble growth resulting from increased water vapour pressure at the die nozzle (Hagenimana *et al*., 2006). The results suggest that low feed moisture and high screw speed would be important for attainment of high expansion of extrudates.

Bulk density is related to the extent of extrudate expansion (Hagenimana *et al*., 2006) and is very important in the production of expanded and formed food products. Increases in feed moisture at low die temperatures (<130 °C) and high feed moisture at high die temperatures (>145°C) resulted in increased bulk density (Table 3; Fig. 1). High bulk density at high feed moisture was probably due to the lubricating and plasticizing effect of water, which lowers the mechanical shear effects and disruption of starch in the extruder (Altan & Maskan, 2011). High bulk density could also be due to rupture of the starch cell walls caused by fibre particles before the gas bubbles in the starch attained full expansion (Altan & Maskan, 2011; Chiu, Peng, Tsai, Tsay, & Lui, 2013). Chiu *et al* (2013) reported that high bulk density may result from binding of water to non-starch polysaccharides (fibre) which inhibits water loss at the die thus reducing expansion. Low bulk density at high screw speed (Fig. 1b and 1c) for all temperatures was probably due to starch gelatinization and increased expansion of extrudate caused by increased water vapour pressure at the die (Hagenimana *et al*., 2006).

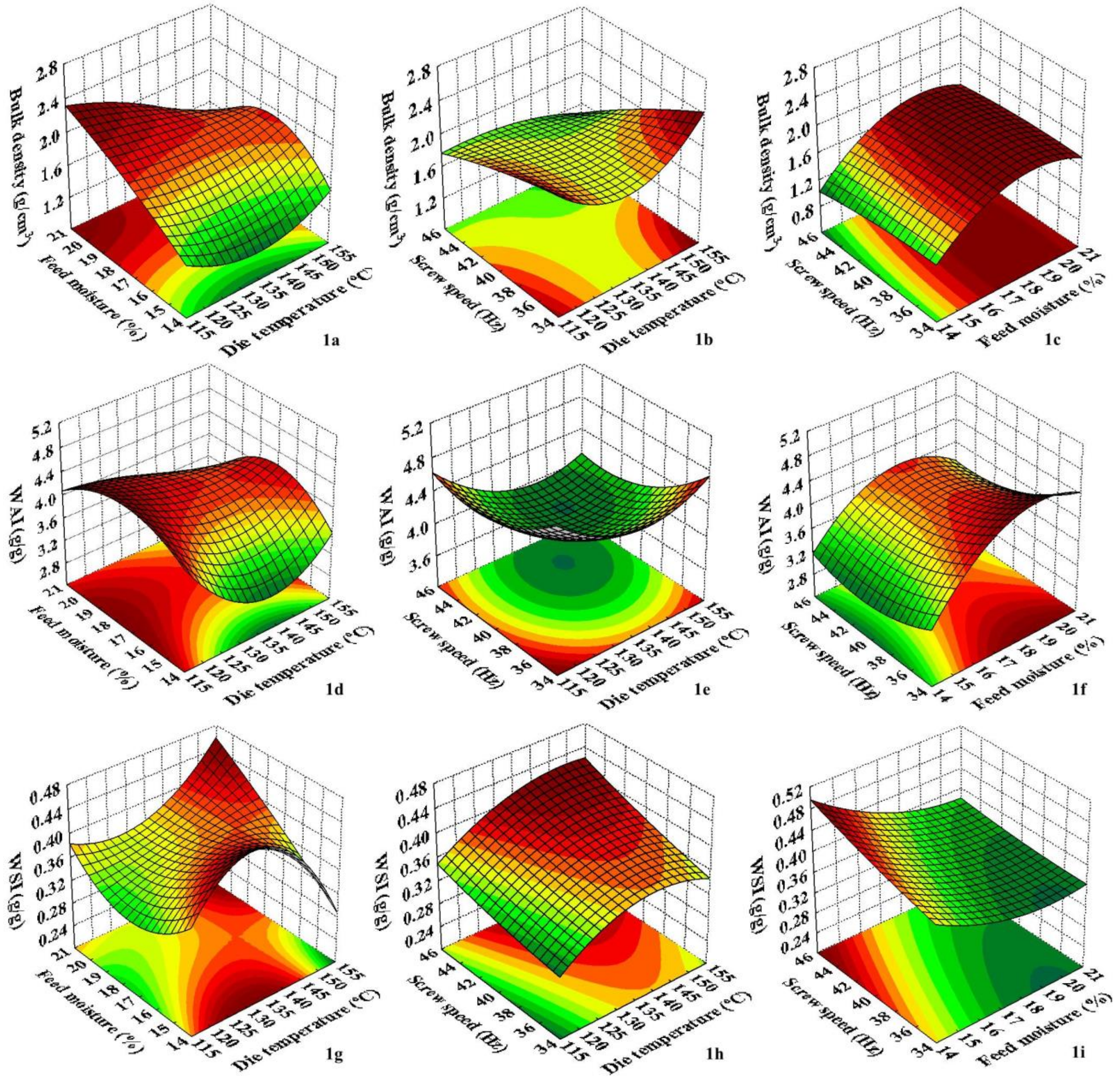

Figure 1a to 1h Response surfaces curves of bulk density, WAI and WSI as affected by die temperature, feed moisture and screw speed

In this study it is notable that high bulk density was a function of increase in feed moisture (linear terms) and the interactions of feed moisture (linear terms) with die temperature (Table 4). Low feed moisture and high screw speed therefore would be necessary for obtaining an extrudate with low bulk density.

Water absorption and solubility index

Water absorption index (WAI) was significantly influenced by feed moisture in both linear and quadratic terms, screw speed (linear terms) and the interaction of die temperature and feed moisture (Table 4, Fig. 1d to 1f). The negative coefficients of the linear terms of screw speed, quadratic terms of feed moisture and interaction terms of die temperature and feed moisture indicate that WAI decreases with increase of those variables. Positive coefficients of the linear terms of feed moisture indicated that WAI increased with increases in feed moisture. The increase in WAI with increasing feed moisture could be attributed to the dispersion of starch in excess water, the increased degree of starch damage by gelatinization and the extrusion induced fragmentation of starch granules (Chiu *et al*., 2013; Ding, Ainsworth, Tucker, & Marson, 2005; Hagenimana *et al*., 2006; Yagcı & Gögüs, 2011). High moisture content builds low viscosity, thus allowing for internal mixing and uniform heating of the dough which would account for enhanced gelatinization (Yagcı & Gögüs, 2011). Additionally, protein denaturation, starch gelatinization and swelling of fibre at high feed moisture could be responsible for increase in WAI (Altan & Maskan, 2011).

Increases in die temperature (linear) and interactions of die temperature and feed moisture (linear and quadratic terms) caused increase in WSI, while increases in feed moisture (linear) resulted in reduction of WSI (Table 3). Similarly increases in screw speed caused significant increase in WSI at low feed moisture and at high die temperature (Fig. 1h and 1i). Increase in WSI at high die temperatures was probably associated with the disintegration of starch granules and low molecular compounds from extrudate melt during the extrusion process, thus increasing the soluble material.(Yağcı & Göğüş, 2008) The increase in WSI with increase in screw speed was in agreement with previous works (Altan & Maskan, 2011; Altan *et al*., 2008) and may be due to increased specific mechanical energy, mechanical shear and degradation of macromolecules. Increased WSI at high temperature and high screw speed (Fig. 1h) was possibly associated with the starch degradation at high temperature and greater shear action at high screw speed (Altan & Maskan, 2011; Seth, Badwaik, & Ganapathy, 2015)

High WSI at high feed moisture could be explained by the complete changes of food components from native forms, that is starch gelatinization and protein denaturation, respectively (Yu, Liang; Ramaswamy, 2012). The low WSI at high feed moisture and low die temperature, as well as at low screw speed and low die temperature could be explained by the low degree of starch transformation, the reduced shear degradation of starch and the low tendency to dextrinization (Hernandez-Diaz, Quintero-Ramos, Barnard, & Balandran-Quintana, 2007; Liu *et al.*, 2011). High moisture content in extrusion processes may reduce protein denaturation and starch degradation (Hernandez-Diaz *et al.,* 2007). Alternatively, high feed moisture acts as a plasticizer thus hindering full expansion and rupture of starch in the extruder (Liu *et al*., 2011). WSI is an indication of the ease of solubilization and extent of water absorption of the cooked product (Altan & Maskan, 2011). While WAI measures the volume occupied by starch after swelling in excess water, thus its integrity in aqueous dispersions (Ding et al., 2005). Both WAI and WSI can be useful indicators of the suitability for use of extruded starchy products in suspensions or solutions (Yagcı, & Gögüs, 2011). Results from this study were in agreement with Ding et al., (2006) who reported increases in WSI as extrusion temperature increased at feed moisture of 18.2%. High WAI obtained at moderate feed moisture and low-to-high die temperatures possibly reflected the ability of Roba1 extrudate to absorb moisture and the stability of starch polymer composites upon exposure to water treatment;

which would be a good attribute in flour applications for aqueous dispersions (Sarifudin & Assiry, 2014) such as soups and gruels. This study therefore reveals that both extrusion conditions and material composition appear to influence the functional properties of bean extrudates (WAI, WSI, bulk density and expansion).

Extrudate texture

The hardness, crunchiness and crispiness of Roba1 extrudates measured in terms of peak force and area under force deformation curve were determined. Peak force represents the resistance of extrudate to initial penetration and is believed to be the hardness of the extrudate (Anton & Luciano, 2007; Ding *et al*., 2006). The regression model of extrudate hardness was significant as a function of screw speed (linear terms), feed moisture (quadratic terms), and the interactions of feed moisture with die temperature (Table 4). High screw speed and low feed moisture resulted in soft extrudates. Increase in feed moisture at low die temperatures resulted in increased extrudate hardness (Fig. 2 and 3).

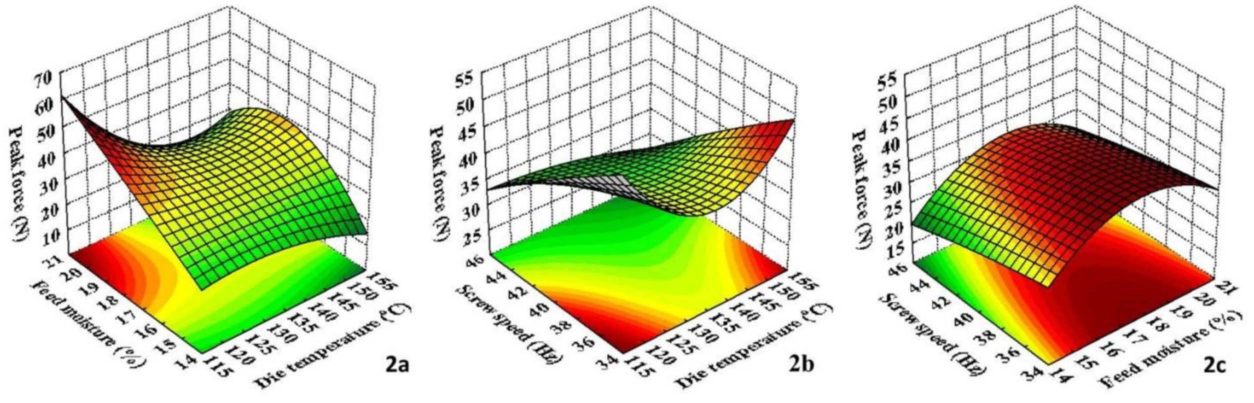

Figure 4 Response surfaces showing effect of die temperature, feed moisture and screw speed on peak force (hardness) of Roba1 extrudate

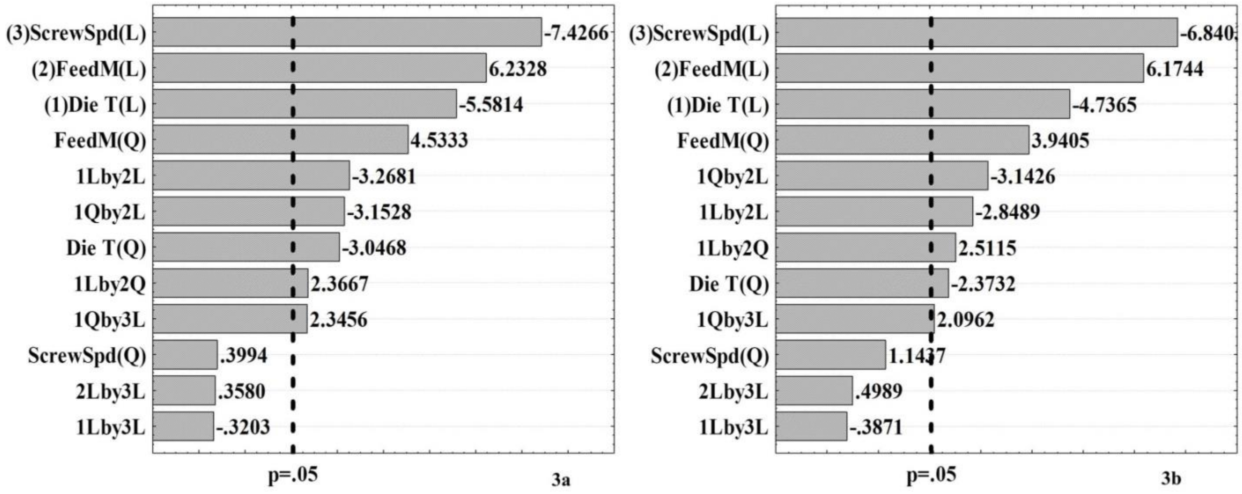

Figure 5 - 6 Pareto charts showing significance of effects of extrusion conditions on Roba1 extrudate hardness and crispiness.

Positive coefficients of feed moisture (LT and QT) and interactions of die temperature (QT) with screw speed resulted in increased extrudate hardness (Table 4, Fig. 3). This could partly be due to the reduced dough friction in the extruder, permitting rapid extrusion and full expansion of extrudate at the die exit at high temperatures (Hagenimana et al., 2006). Increase in screw speed (LT) significantly (p < 0.05) decreased Roba1 extrudate hardness, particularly at low feed moisture and high die temperature (Figures 2b, 2c, and 3). Low hardness, a favoured property of extrudates (Meng et al., 2010), was observed at low feed moisture and high screw speed. Results from this study are similar to reports from previous works (Altan *et al.*, 2008; Ding *et al.*, 2005), which showed that extrudate hardness increased with increase in feed moisture at low die temperatures. This may be due to the reduced pressure resulting from lubrication of extruder walls at high feed moisture, thus lowering expansion. The hardness of extrudates was highly related to the bulk density (Fig. 1 and 2). Low screw speed resulted in harder extrudates, which probably was due to increase in melt viscosity of the mix (Ding *et al.*, 2006; Maskus & Arntfield, 2015).

The area under the force determination curve (Table 2) represents the energy required for a given displacement and can measure the crispiness and brittleness in texture of a product (Anton & Luciano, 2007). Roba1 extrudate brittleness tended to increase with increase in screw speed (LT, $p < 0.01$) and decrease in feed moisture (QT, $p < 0.001$)(Table 4; Figure 3b). Increase in die temperature (QT) increased the crispiness of Roba1 extrudate. Interactions between die temperature (quadratic) and feed moisture (linear) significantly ($p < 0.05$) decreased the area under the force-deformation curve (Table 4; Fig 3b), thus increased the brittleness/crispiness of extrudate. Die temperature (QT) and screw speed (LT) interaction significantly ($p < 0.05$) increased the extrudate crispiness. The results suggested that low feed moisture (QT), high screw speed (LT) and die temperature-feed moisture interactions during bean extrusion result into soft crispy extrudates, which is in agreement with Altan et al., (2008) and Ding et al., (2006) who reported similar findings.

3.2 Multi-response desirability optimization of Roba1 extrusion conditions and extrudate properties

Optimal extrusion conditions that simultaneously satisfied all selected extrudate responses and could improve the efficiency of the process for Roba1 snack extrudate were identified (Fig. 4). Notable, individual optimal desirability values (d) (Fig. 4) differed from those obtained with a global optimal desirability (D). This was due to the conversions that occurred statistically to reach a simultaneously optimal values (Tumwesigye et al., 2016; Vera Candioti et al., 2014).

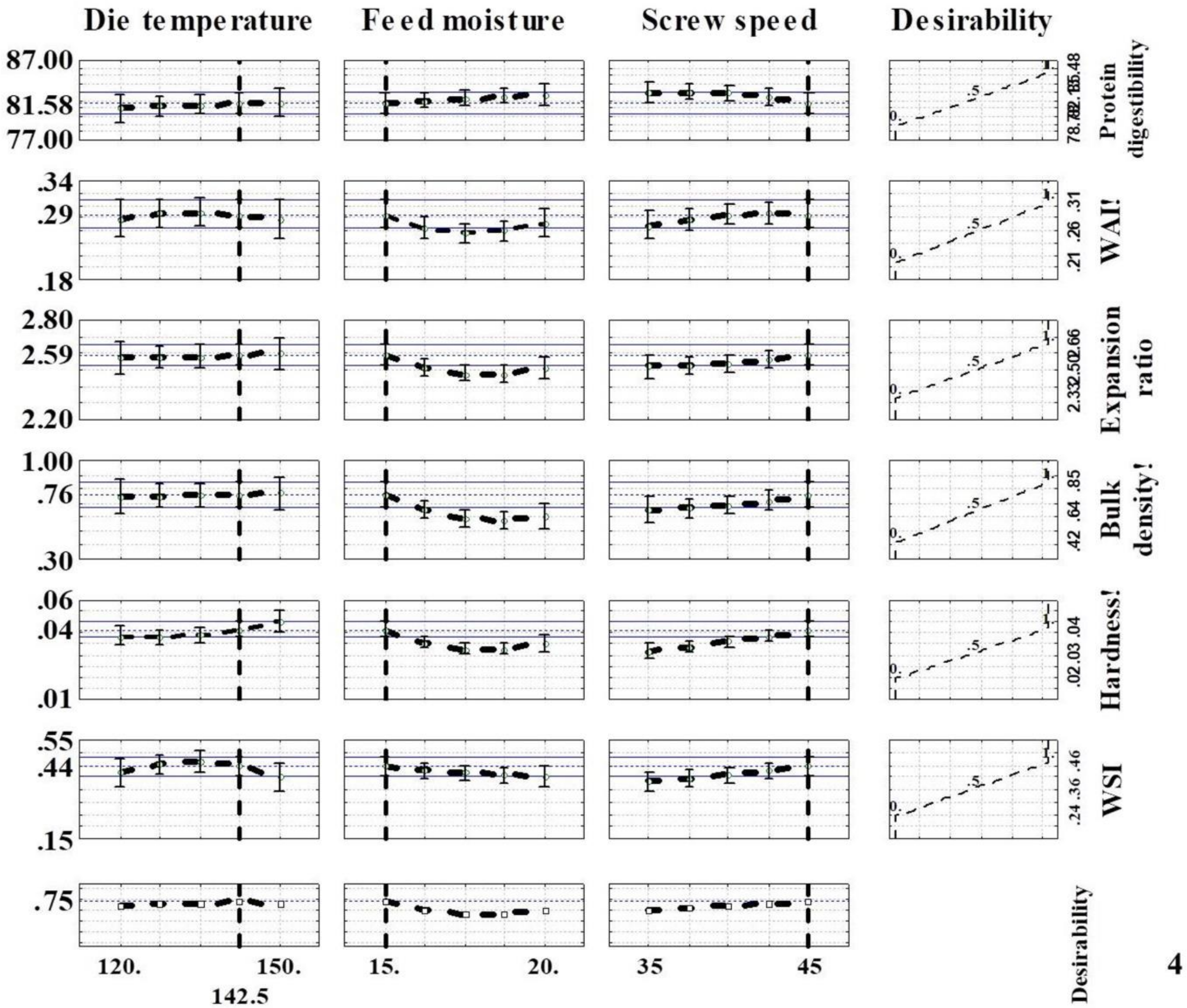

Figure 7 Desirability index and predicted response variables in multi-response optimization of Roba1 extrusion conditions and product properties

Results revealed that die temperature 142.5 °C, feed moisture 15 % and screw speed 45 Hz, were sufficient for producing best characteristics for Roba1extrudate with bulk density 1.32 g/cm^3, expansion ratio 2.60 and hardness 24.4 N at optimal desirability of 0.75. High expansion, low bulk density and hardness were identified as important attributes in extruded beans snack processing, properties also established by previous workers (Altan & Maskan, 2011; Jyothi, Sheriff, & Sajeev, 2009; Maskus & Arntfield, 2015). These findings show that low feed moisture and high screw speed are essential for obtaining bean snack extrudate with desirable expansion, hardness, bulk density and protein digestibility.

CONCLUSION

The results of this study revealed that die temperature, feed moisture and screw significantly influenced Roba1 bean extrudate properties. Regression coefficient (R^2) values showed significant effect of individual factors and their interactions in influencing bean extrudate properties. Increases in WAI, bulk density and extrudate hardness and reductions in expansion and WSI were a function of the linear, quadratic and interaction relationships of feed moisture, die temperature and screw speed. Low feed moisture and high screw speed were found essential to produce a soft crispy snack extrudate with low bulk density and high water solubility index. Die temperature 142.5 °C, feed moisture (15%) and screw speed 270 rpm were found as optimal process conditions for producing an expanded snack extrudate from Roba1 bean with optimal desirability >0.7. Results of this study therefore can be very important for application in the food industry, providing extrusion conditions that for generating acceptable and nutritious products. This in turn will contribute to increased diversity of bean products on the market, reduce monotony and overcome the challenge of hard-to-cook defects. Subsequent inclusion of Roba1 beans in extruded snacks shall increase protein, fibre and mineral intake by the consumers.

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Highlights

- Optimal extrusion conditions for Roba1 bean snack extrudate were determined
- Extrusion conditions linear, quadratic and interaction terms were significant
- High extrudate bulk density and hardness were associated with high feed moisture

- High screw speed and die temperature resulted in increased extrudate expansion

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