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Optimization of extrusion conditions for development of fish-maize based extruded snacks by response surface methodology

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Abstract

The aim of this work is to study the extrusion process and optimum conditions for development of maize-fish based extruded snacks by using Design-Expert® software for Response Surface Methodology (RSM). However, there are still low developed maize-fish extruded products on the market. Mixture of maize flour and dried fish powder was used. Effect of main extrusion conditions like feed moisture, barrel temperature and screw speed were studied. Product responses such as Specific Mechanical Energy (SME), Expansion Ratio (ER), Bulk Density (BD), Water Absorption Index (WAI), Water Solubility Index (WSI) and hardness (H) were estimated and studied using RSM. Maize-fish flour mixture was extruded at moisture content (14-18%), screw speed (400-550 rpm) and barrel temperature (125-175 °C). There was a significant effect of feed moisture on all of the estimated responses. Screw speed had significant effect on ER, BD, WSI and hardness of extrudates while barrel temperature had significant effect on SME, ER, WSI and hardness. By increasing the feed moisture BD and hardness increased but SME, ER, WAI and WSI decreased. Increasing the screw speed resulted in reducing BD and hardness, but ER and WSI both were increased. By increasing barrel temperature SME and hardness were reduced while ER and WSI both were increased. Optimization of extrusion conditions for snacks processing was 14.27-15.12% feed moisture content, 400-463 rpm of screw speed and 173.61 °C of barrel temperature.

Keywords: *Extrusion cooking, Fish, Maize, Response Surface Methodology (RSM), Optimization.*

1. Introduction

Food processing techniques had enhanced the nutrient bioavailability, storage stability, safety, relishing, and convenience of foods. Extrusion technology is one of the most widely used techniques due to low cost, simplicity, processing flexibility. Extrusion cooking is a High Temperature Short residence Time (HTST) process by which moistened starchy and proteinaceous materials are plasticized and cooked in a tube by combination of high pressure, intense mechanical shear and heat to create fabricated, shaped products of varying texture.

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Extruded snack like products are mostly cereal-based and developed mainly from corn, wheat and rice (Singh *et al.*, 2014).

Extrusion converts commodities, usually in a granular or powdered form, into fully cooked, shelf-stable food products with enhanced textural attributes and flavor primarily in the cereal, dairy, bakery, confectionery and pet food industries (Patil *et al.*, 2007, and Berrios *et al.*, 2008). Extrusion offers numerous advantages including versatility, high productivity, low operating costs, energy efficiency, high quality of resulting products and an improvement in digestibility and biological value of proteins (Gutiérrez-Dorado *et al.*, 2008).

Snacks industry is an important and modern sector which has a promising and admirable future, global snack foods market increases proportionally and forecast to reach $334 bn and 48,519 thousand tons in volume terms, by the year 2015. The Indian snack foods market is worth around $3 bn and has an annual growth rate of 15-20% (Singh *et al.*, 2014).

Maize or corn is the third crop in importance, after wheat and rice, as a staple human food; provides about 50% of the proteins and calories in the diet of developing countries. Maize kernel contains 69.6-74.5% (dw) carbohydrates, 7.7-13.6% (dw) proteins, 3.2-7.7% (dw) fats, and some vitamins (B complex) and unsaturated fatty acids (oleic, linoleic). There is a marked deficiency of Lys and Trp, a moderate deficiency of Ile, and an excess of Leu, a constellation contributing to development of pellagra or florid kwashiorkor. Phytochemicals such as phenolic compounds, amongst others have also been reported on several maize genotypes. Maize has a higher antioxidant activity when compared to wheat, oat, and rice (Adom and Liu, 2002).

As the protein-energy-malnutrition problem continues to worsen in the face of limited protein sources, the effective use of readily available and inexpensive sources of protein has become a major focus of research in recent years (Plahar *et al.*, 2003). Traditional snacks are based on cereals such as maize, rice and wheat which are low in protein content and usually were fortified with pulse protein to produce nutritious snack foods without adequate supplementation with high quality protein (Mohamed *et al.*, 2014).

Despite the high protein contents of fish products there is inadequate use in snacks processing. Fish are not only excellent sources of high nutritional value protein, but also excellent sources of lipid that contains omega-3 fatty acids, especially, Eicosapentaenoic acid (EPA) and Docosahexaenoic acid (DHA). The omega-3 fatty acids are essential for normal growth and development, and may prevent or moderate coronary artery disease, hypertension, diabetes, arthritis, others inflammatory and autoimmune disorders, as well as cancer (Kris-Etherton *et al.*, 2002).

Response Surface Methodology (RSM) is a collection of experimental design and optimization techniques that enables the experimenter to determine the relationship between the responses and the independent variables. RSM is typically used for mapping a response surface over a particular region of interest, optimizing the response, or for selecting operating conditions to achieve target specifications or customer requirements (Myers and Montgomery, 2002).

Successful incorporation of fish powder into starch-based materials by extrusion will improve biological value of snacks. Extrusion requires controlling different variables like feed moisture, barrel temperature and screw speed which affect the properties of the final product. The purpose of this investigation was to develop high protein extruded snacks based on maize-fish by using extrusion technology. This was achieved through process standardization, sensory evaluation and optimization of extrusion conditions.

2. Material and methods

2.1. Extrusion

Extrusion was performed with a laboratory-scale co-rotating twin-screw extruder (Model BC 21, Clextral, Firminy, Cedex, France) shown in Figure 1. The barrel diameter and its length to diameter ratio (L/D) were 25 mm and 16:1, respectively. Twin-screws (400 mm) had segmental elements ranging from 5 to 50 mm with gradual decreasing pitch. A “conveying screw configuration” with a combination of feed screws and Reverse Screw Element (RSE) with groove as shown in Figure 1 and Table 1 was used. The barrel which housed the twin screws had 400 mm length with four barrel zones of 100 mm each. The barrel zone at the feed hopper was not heated and was maintained at 35-40 °C by cooling water. Temperature of the second and third zones were maintained at 70 and 100 °C respectively throughout the experiments, while the temperature at last zone (compression and die section) was varied according to the experimental design. The diameter of die opening selected was 5 mm. The extruder was powered by an 8.5 kW motor with speed variable from 0 to 682 rpm. The extruder was equipped with a torque indicator, which showed percent of torque in proportion to the current drawn by the drive motor. Raw material was metered into the extruder with a single screw volumetric feeder (D.S. and M, Modena, Italy). The extruder was thoroughly calibrated with respect to the combinations of feed rate and screw speed to be used. The feed rate was varied for optimum filling of the extruder barrel corresponding to the screw speed. The moisture content of feed was varied by injecting water into extruder with water pump. A variable speed die face cutter with four bladed knives was used to cut the extrudates. The extrudates were dried, packed in polythene bags and stored in airtight containers for further analysis of physicochemical properties.

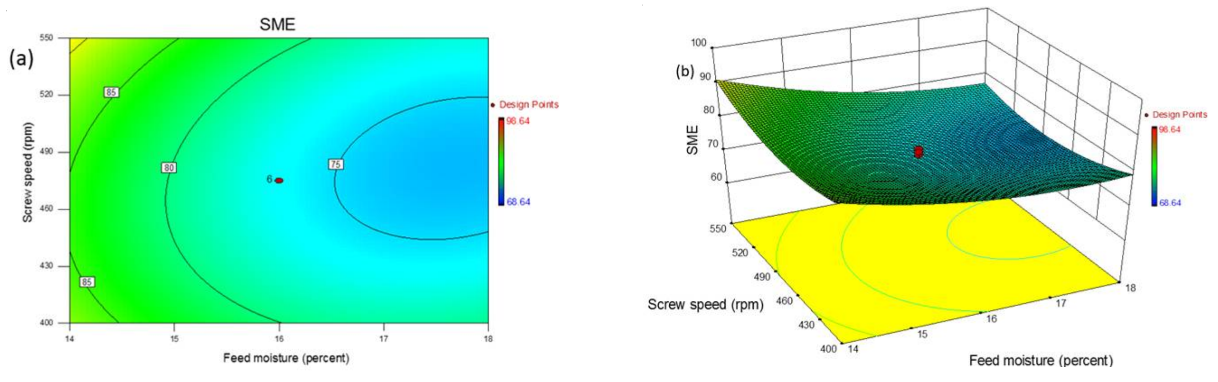

Figure 1: Contour (a) and its response surface plot depicting the behavior of expansion ratio (ER) at different screw speed and barrel temperature while the other processing variables are at center point

Table 1: Screw configuration in different sections of the extruder (From hopper to die)

Screw section	1	2	3	4	5	6	7	8	9	10
Screw element	BAGUE	*C2F	*C2F	*C2F	*C2F	*C2F	†INO0	**C1F	#CF1C	**C1F
Length (mm)	20	50	50	50	50	50	5	50	25	50
Pitch (mm)	-	50	33.33	25	25	16.7	-	16.66	12.5	12.5

Note: *C2F – Conjugated section 2 threads, supply and transport; **C1F – Conjugated section 1 thread, transport and compression of the material; #CF1C – Conjugated screw segment section 1 thread, screw segment with groove; and †INO0 – Interface rings between C2F and C1F, connection interfaces between sections.

2.2. Raw materials

Fish powder was prepared from Indian major carp (Cirrhinus mrigala) that was procured from College of Fisheries, Guru Angad Dev Veterinary and Animal Sciences University (GADVASU), Ludhiana, Punjab, India. The fish were de-scaled, beheaded, eviscerated and washed with potable water. The dressed fish was cooked by boiling in water at 100 °C for 10–12 min under normal atmospheric pressure. The cooked fish was 10 °C, de-skinned and de-boned manually. The separated cooked meat was dried in an electrically heated cabinet drier at 43-45 °C. The dried fish muscle was powdered in a modern laboratory mixer (rotor motor: 3000 rpm; Rotor motor 2.25 Kw; pan motor: 0.6 Kw; pan speed: variable to 50 rpm, overall dimensions: 100 cm). The fish flour was packed in polythene pack after sieving and stored in refrigerator till preparation of blend (Singh *et al*., 2014b). Maize was procured from specialty market and ground to pass through 200 μ sieve using lab mill (Perten Intruments, Hagersten, Sweden). Several preliminary trials were made to select the proportion of fish flour incorporation in maize flour. The maize flour was mixed with the fish flour in the proportion of 850:150 gm in the ribbon blender (G L Extrusion systems, New Delhi, India) for 15 min to ensure uniform mixing. Salt was added at 2% into the mix and again blended for 10 min (Shaviklo *et al*., 2011).

2.3. Compositional analysis

The proximate composition (moisture, ash, protein and fat) analysis of raw materials and extrudates was determined using the standard procedures of AOAC (2000), carbohydrates were calculated by difference. All the experiments were replicated, so that the data in the paper are expressed as the mean (± SD) of triplicate analysis.

2.4. Product responses

2.4.1. Specific Mechanical Energy (SME)

SME (Wh / kg) was calculated from rated screw speed, motor power rating (8.5 kW), actual screw speed, % motor torque and mass flow rate (kg / h) using the following formula (Pansawat *et al.*, 2008).

$$SME\left(\frac{Wh}{Kg}\right)=\frac{ASS}{RSS}\times\frac{\%MT}{100}\times\frac{MPR}{MFR}\times 1000 \qquad ...(1)$$

where *SME*, *ASS*, *RSS*, *%MT*, *MPR*, *MFR* are Specific Mechanical Energy in *Wh/kg*, actual screw speed (rpm), percent motor torque, motor power rating (KW), and mass flow rate (kg / h), respectively.

2.5. Expansion ratio (ER)

For determination of ER, the cross sectional diameter of the extrudates was measured with a Vernier caliper. The ER was calculated as the cross sectional diameter of the extrudate divided by the diameter of the die opening (Ding *et al.*, 2005).

2.6. Bulk Density (BD)

The density (g / cc) of extruded snacks was measured by using a 100 ml graduated cylinder by rapeseed displacement. The volume of 20 g randomized samples were measured for each test. The ratio of sample weight and the replaced volume in the cylinder was calculated as density (Pan *et al.*, 1998; and Patil *et al.*, 2007).

$$D\left(\frac{g}{ml}\right)=\frac{Weight\ Extrudates\,(kg)}{Volume\ Displayed\ by\ Extrudates\,(ml)} \qquad ...(2)$$

2.7. Water Absorption Index (WAI)

WAI of the snacks was determined by method outlined by Anderson *et al.* (1970). The WAI measures the volume occupied by the granule or starch polymer after swelling in excess of water. The ground extrudates were suspended in distilled water at room temperature (34 °C) for 30 min, gently stirred during this period, and then centrifuged at 3000 × g for 15 min. The supernatant liquid was poured carefully into evaporating dish. The remaining gel was weighed and WAI was calculated as the grams of gel obtained per gram of solid.

$$WAI\left(\frac{g}{g}\right)=\frac{Weight\ of\ Sediment\,(g)}{Weight\ of\ Dry\ Solids\,(g)} \qquad ...(3)$$

2.8. Water Solubility Index (WSI)

WSI determines the amount of free polysaccharides or polysaccharides released from the granule on addition of excess water. The WSI was the weight of dry solids in the supernatant from the WAI test described above (Anderson *et al.*, 1969) expressed as a percentage of the original weight of the sample.

$$\%WSI=\frac{Weight\ of\ Disolved\ Solid\ in\ Supernatant}{Weight\ of\ Dry\ Solids} \qquad ...(4)$$

2.9. Hardness

Textural quality of the snack samples was examined by using a TA-XT 2i Texture Analyzer (Stable Microsystems, Surrey, UK). The compression probe (50 mm dia., aluminum cylinder) was applied to measure the compression force required for samples breakage which indicates hardness. Testing conditions were 1.0 mm / s pre-test speed, 2.0 mm / s test speed, 10.0 mm / s post-test speed and 5 mm distance (Singh *et al.*, 2015).

2.10. Experimental design and statistical analysis

The optimum conditions for extrusion of fish-maize based snack products were determined by RSM. Based on the results of preliminary studies, the experiments were optimized using three independent variables and five levels central composite design (CCD). The independent variables considered in this study were moisture, screw speed and barrel temperature. RSM was applied for experimental data using a commercial statistical package, Design-Expert (version 9.0.3.1, May 2014, Stat-Ease, Inc., Minneapolis, MN, USA) for the generation of response surface plots. The same software was used for statistical analysis of experimental data. RSM was used to investigate effects of extrusion cooking conditions on the product properties of fish and maize blends.

The results were analyzed by a multiple linear regression method which describes the effects of variables in the models derived. Experimental data were fitted to the selected models and regression coefficients were obtained. The Analysis of Variance (ANOVA) tables were generated for each of the response functions. The individual effect of each variable and also the effects of the interaction terms were determined. The design required 20 experimental runs with eight factorial points, six star corner points and six center points. Experiments were randomized in order to minimize the systematic bias in observed responses due to extraneous factors.

2.11. Optimization

Extrusion processing parameters were optimized by using a conventional graphical method of RSM in order to obtain extrudates with acceptable properties. The main criteria for constraints optimization were ER and WAI to be maximized while BD and hardness to be minimized and WSI to be in range. Contour plots were obtained as a result of superimposing or overlaying of contour plots from which one can determine optimum process variables range for extrusion of product with specified properties.

3. Results and discussion

Physical properties of extruded snacks are given in Table 2. ANOVA and model statistics for the dependent variables are presented in Table 3 and regression coefficients are shown in Table 4. The regression models for SME, ER, BD, WAI, WSI and Hardness (H) were highly significant $p \leq 0.0015$ (where values of "Prob > F" less than 0.05 indicate model terms are significant) with a high correlation coefficient ($R^2 = 0.9627$, 0.9236, 0.9112,

Table 2: Effect of extrusion condition on product responses

Std	FM	SS	T	SME	ER	BD	WAI	WSI	H
1	14	400	125	93.25	2.25	0.25	5.35	21.51	66.73
2	18	400	125	85.85	2.06	0.27	5.24	18.64	74.43
3	14	550	125	98.64	2.75	0.24	5.86	22.82	44.64
4	18	550	125	84.64	2.45	0.22	5.68	17.82	60.32
5	14	400	175	84.25	2.81	0.21	6.07	20.69	56.37
6	18	400	175	75.94	2.59	0.31	5.72	21.34	64.34
7	14	550	175	86.37	2.84	0.22	5.54	23.52	40.34
8	18	550	175	73.18	2.52	0.25	5.16	22.34	55.43
9	12.6364	475	150	95.42	2.93	0.19	5.75	20.37	50.34
10	19.3636	475	150	77.18	2.38	0.25	5.06	18.64	74.72
11	16	348.866	150	88.46	2.34	0.25	5.45	19.73	71.34
12	16	601.134	150	89.96	3.06	0.22	5.77	22.65	50.34
13	16	475	107	96.72	1.97	0.27	5.53	17.34	56.43
14	16	475	192	68.64	2.44	0.25	5.69	22.34	44.34
15	16	475	150	78.63	2.57	0.22	5.05	20.73	50.26
16	16	475	150	76.71	2.63	0.24	5.09	21.43	51.37
17	16	475	150	77.64	2.44	0.23	5.25	22.34	52.41
18	16	475	150	74.97	2.43	0.23	5.14	19.64	50.38
19	16	475	150	73.32	2.42	0.25	5.08	20.72	49.61
20	16	475	150	75.63	2.68	0.24	4.92	20.34	50.73

Note: SS, T, and FM: screw speed (rpm), Temperature (°C) and Feed moisture (%).

Table 3: ANOVA and model statistics for the dependent variables

Factors	SME	ER	BD	WAI	WSI	H
F-value	28.68	13.43	11.4	17.77	7.25	107.23
P > *F*	0.0001	0.0002	0.0004	0.0001	0.0015	0.0001
Std. Dev.	2.35	0.1	0.011	0.11	1	1.38
Mean	82.77	2.53	0.24	5.42	20.75	55.74
C.V. %	2.84	4.12	4.38	2.03	4.81	2.48
R^2	0.9627	0.9236	0.9112	0.9412	0.7699	0.9897
Adj. R^2	0.9291	0.8548	0.8312	0.8882	0.6637	0.9805
Pred. R^2	0.7929	0.6985	0.5829	0.7283	0.4256	0.9378
Adeq. precision	17.722	13.586	13.817	12.337	9.746	34.976
Lack of fit	0.2315	0.6555	0.4925	0.4736	0.42	0.1254

0.9412, 0.7699 and 0.9897 for all responses respectively). All selected models in RSM showed no significant lack of fit that means all the second-order polynomial models correlated well with the measured data. The predicted R^2 was close to the adjusted R^2 for all the parameters. Adequate precision measures the signal to noise ratio, a ratio greater than four is desirable. Adequate precision was more than four for all responses that indicates an adequate signal. This model can be used to navigate the design space.

Relationship of independent variable (extrusion conditions) and dependent variable (physical properties of the product) are being discussed as follows:

Table 4: Regression coefficients for fitted models

Response	Intercept	A	B	C	AB	AC	BC	A^2	B^2	C^2
SME	76.1952	–5.3875	0.4439	–6.58	–1.435	–0.0125	–0.6025	3.2932	4.32204	2.01334
p=		< 0.0001	0.5009	< 0.0001	0.114	0.9883	0.4848	0.0003	< 0.0001	0.0087
ER	2.52787	–0.1432	0.1509	0.1494	–0.026	–0.0063	–0.11625	0.047792	0.06370	–0.11131
p=		0.0005	0.0003	0.0003	0.492	0.8685	0.0102	0.112	0.0426	0.0023
D	0.234751	0.0169	–0.012	–0.002	–0.014	0.01625	0.00125	–0.00368	0.00162	0.01046
p=		0.0001	0.0021	0.5573	0.004	0.0014	0.7441	0.2148	0.5705	0.0037
WAI	5.08806	–0.1597	0.0292	0.0461	–0.013	–0.055	–0.255	0.113717	0.18619	0.18619
p=		0.0003	0.3507	0.153	0.754	0.1879	< 0.0001	0.0029	< 0.0001	< 0.0001
WSI	20.7475	–0.8281	0.6759	1.1356	–0.495	0.9175	0.4175			
p=		0.009	0.0264	0.001	0.184	0.022	0.2578			
H	50.8086	6.4028	–7.063	–3.659	1.887	–0.04	1.4075	4.03921	3.4417	–0.2547
p=		< 0.0001	< 0.0001	< 0.0001	0.003	0.9365	0.0165	< 0.0001	< 0.0001	0.501
			0.01 ≤	0.05 ≤ p						
Legend		p ≤ 0.01	p < 0.05	p < 0.10	p ≥ 0.10					

3.1. Specific Mechanical Energy (SME)

SME is the amount of work input from driver motor into the extruded raw material. SME is an important factor for design engineering and directly affects the final product quality, and it is used as a system parameter to model extrudate properties (Harper, 1989, and Godavarti and Karwe, 1997).

A higher amount of SME delivered to the extruded material results in a greater degree of starch gelatinization and extrudate expansion (Pathania *et al.,* 2013). Results given in Table 2 elucidated that SME ranged from 68.64 to 98.64 Wh / kg. Feed moisture and barrel temperature had significant effects on SME ($p < 0.01$) while the effect of screw speed was non-significant. The negative coefficients of the linear terms of moisture and temperature level indicated that SME decreases with increase of these tow variables (Figure 1 and Table 4). A lubricating effect is produced by high moisture resulting in less energy use and subsequently reduced SME. The starch gelatinization of extrudates has been found to increase with increased SME during extrusion (Ilo *et al.,* 1996). Higher temperature facilitates the transformation from solid flow to viscoelastic flow and starch gelatinization and reduces the melt viscosity, which resulted in decrease in SME. Similar finding were reported by Pathania *et al*. (2013).

3.2. Expansion ratio

The amount of expansion in food depends on the difference between the vapor pressure of water and the atmospheric pressure, as well as the ability of the exiting product to sustain expansion (Singh *et al.,* 2014b).

Data shown in Table 2 illustrate that ER ranged from 1.97 to 3.06 g / cm3. From regression coefficients table it is clear that feed moisture, screw speed and barrel temperature had high significant effects on ER at $p < 0.01$.

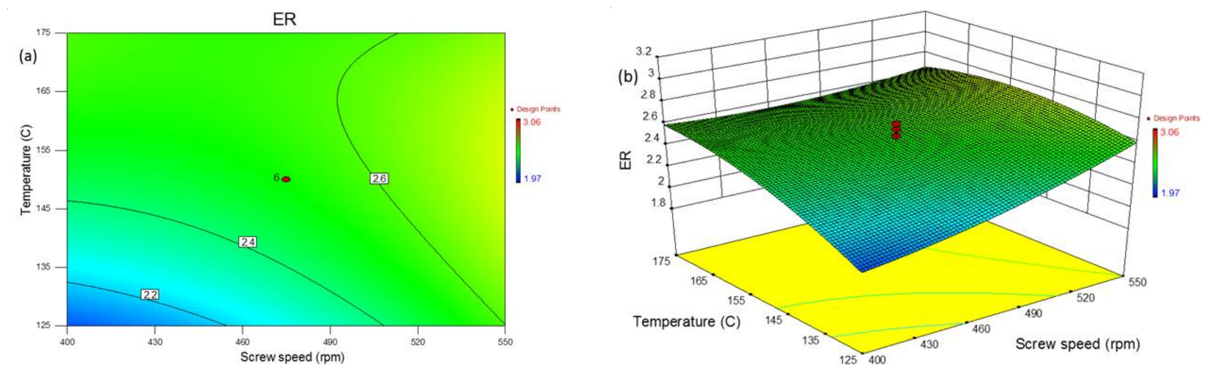

Figure 2 Contour (a) and its response surface plot depicting the behavior of expansion ratio (ER) at different screw speed and barrel temperature while the other processing variables are at center point

The negative coefficients of the linear terms of feed moisture indicated that ER decreases with increase of feed moisture while positive coefficients of screw speed and barrel temperature indicated that ER increased with increasing of these two variables. The interactions between screw speed and temperature ($p < 0.01$) were found to have significant negative correlation with expansion values (Figure 2). During extrusion, moisture in the feed is superheated and the vapor pressure created provides most of the force, which causes expansion once the product is released to ambient pressure and temperature (Sukumar and Athmaselv, 2019). The ER decreases with the decrease of screw speed. This behavior could be explained by the development of less shear force and less pressure within the barrel (Singh *et al*., 2014b).

The expansion index was found to be low at low extrusion temperatures, increasing gradually as the temperature was increased (Plahar *et al.,* 2003). Feed moisture had an influence on elasticity characteristics of the starch-based material, increasing feed moisture during extrusion may reduce the elasticity of the dough through plasticization of the melt, resulting in reducing SME subsequently reducing gelatinization and ER of extrudate (Pathania *et al.,* 2013).

3.3. Bulk density

Figure 3 shows the effect of extrusion conditions on bulk density BD. It was ranged between 0.19 and 0.31 g / cm^3. Effect of the independent variable on BD was opposite as that of ER.

It was found that feed moisture and screw speed had high significant effects on BD ($p < 0.01$) while barrel temperature had no significant effect. The positive coefficients of the linear terms of feed moisture in Table 4 emphasize that BD arises by increasing the feed moisture while negative coefficients of screw speed indicated that BD reduced by increasing screw speed, these findings were matched with latest reported by Singh *et al.* (2015).

The interaction between feed moisture and screw speed had significant negative correlation with density while the interaction between feed moisture and temperature had significant positive correlation (Figure 3). The high dependence of BD on feed moisture would reflect its influence on elasticity characteristics of the starch-based material. Increasing moisture may reduce the elasticity of the dough through plasticization of the melt, resulting in reduced SME and therefore reduced gelatinization, decreasing the expansion and increasing the BD of extrudate (Mercier and Fillet, 1975). Higher screw speeds may be expected to lower melt viscosity of the mix increasing the elasticity of the dough, resulting in a reduction in the density of the extrudate. This effect has been reported previously Fletcher *et al. (*1985).

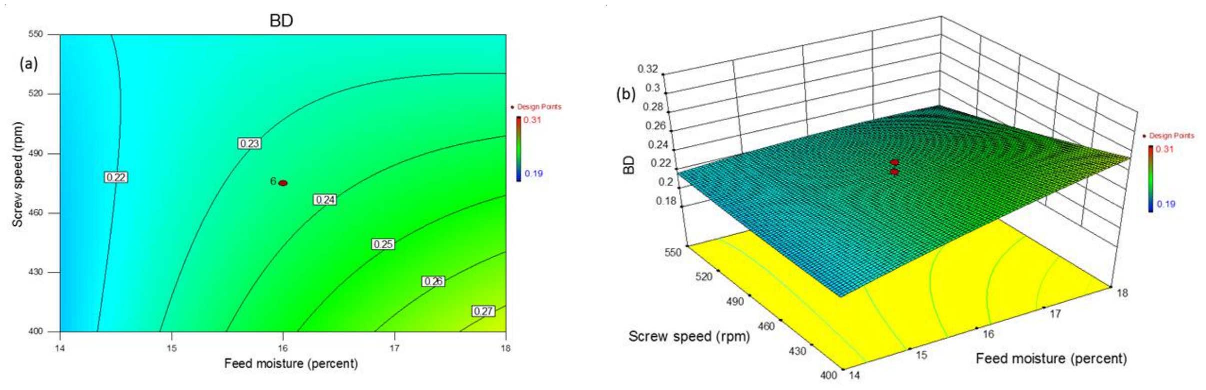

Figure 3: Contour (a) and its response surface (b) plot depicting the behavior of Specific mechanical energy(SME) at different feed moisture content and screw speed while the other processing variables are at center point

3.4. Water Absorption Index (WAI)

WAI measures the water holding by the starch after swelling in excess water, which increases by the degree of starch damage due to extrusion- induced fragmentation of amylose and amylopectin and corresponds to the weight of the gel formed (Mason and Hoseney 1986; and Yaðcý and Göðüþ, 2008).

Results given in Table 2 show that WAI ranged between 4.92 and 6.07 g/g. Feed moisture had high significant effect on WAI ($p < 0.01$). The negative coefficient of the linear terms of feed moisture illustrates that WAI

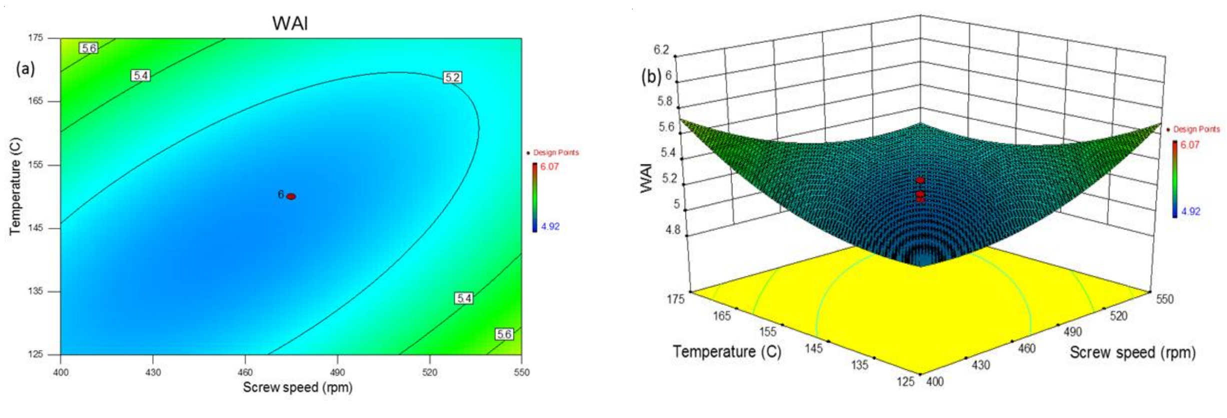

Figure 4: Contour (a) and its response surface plot (b) depicting the behavior of Water Absorption Index (WAI) at different barrel temperature and screw speed while the other processing variables are at center point

significantly decreased with increasing feed moisture. The interactions between screw speed and temperature ($p < 0.01$) were found to have significant negative correlation with WAI values (Figure 4). Gelatinization, the conversion of raw starch to a cooked and digestible material by application of water and heat is one of the important effects of extrusion on the starch component of food (Pathania *et al.*, 2013). The WAI measures the amount of water absorbed by starch after swelling in excess water and can be used as an index of gelatinization, since native starch does not absorb water at room temperature (Yaðcý and Göðüþ, 2008). Water acts as a plasticizer in the extrusion of starch resulting in a higher capacity of water absorption. WAI depends on the availability of hydrophilic groups which bind water molecules and on the gel-forming capacity of macromolecules (Gomez and Aguilera, 1983).

3.5. Water Solubility Index (WSI)

The WSI reflects the amount of soluble polysaccharides released from the starch after extrusion which is related to dextrinization. WSI can be used as an index for the degradation of molecular compounds and measures the degree of starch conversion during extrusion (Ding *et al.*, 2006). Results given in Table 2 show that WSI values ranged between 17.34 and 23.52%. WSI was affected significantly by feed moisture, screw speed and barrel temperature ($p < 0.01$). The negative regression coefficient of the linear terms of feed moisture illustrates that WSI significantly decreased with increasing feed moisture that means increase in the water soluble molecules if the extrusion process was done at low feed moisture (Silva *et al.*, 2009).

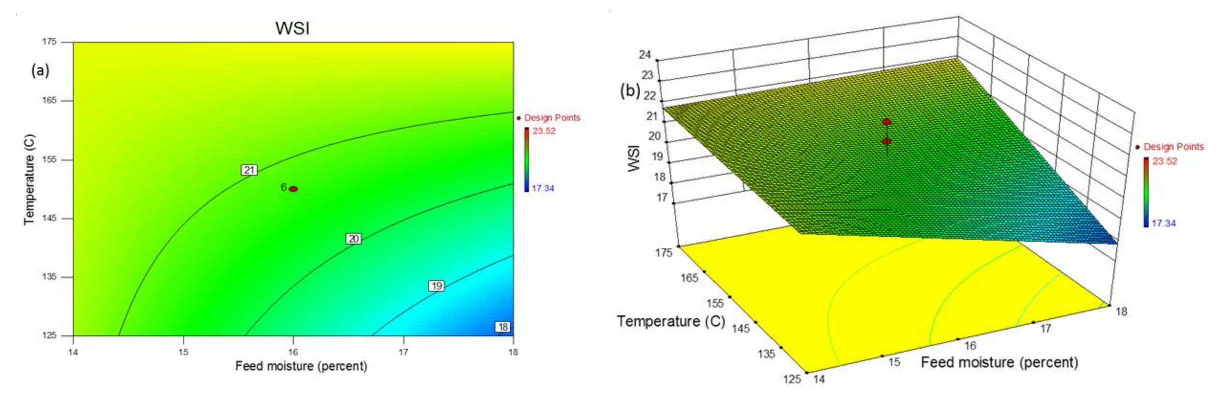

Figure 5: Contour (a) and Response surface (b) plot depicting the behavior of Water Solubility Index (WSI) at different feed moisture and barrel temperature while the other processing variables are at center point

On the other hand, positive regression coefficients of screw speed and barrel temperature mentioned that WSI increases by increasing these two variables. Interactions between moisture and temperature had significant positive correlation ($p < 0.05$) (Figure 5). The combination of harsh conditions and low moisture contents caused an increase in the amount of degraded starch granules resulting in an increased formation of water soluble product; this may be occurred due to the greater shear fragmentation of the starch during extrusion at low moisture contents (Pathania *et al.*, 2013).

Higher moisture content in extrusion process can diminish protein denaturation which subsequently lowers WSI values (Badrie and Mellowes, 1991). Increasing screw speed resulted in high mechanical shear that lead to breakdown of macromolecules to small molecules with higher solubility subsequently increasing WSI that matched with other findings reported by Doğan and Karwe (2003), Singh *et al.* (2015). Increasing temperature would increase the degree of starch gelatinization that could increase the amount of soluble starch resulting in an increase in WSI (Ding *et al.*, 2005).

3.6. Hardness

Data given in Table 2 show that hardness values ranged between 40.34 and 74.72 N. Referring to regression coefficients; hardness was high significantly influenced by feed moisture, screw speed and barrel temperature ($p < 0.01$).

The positive coefficients of the linear terms of feed moisture indicated that hardness increases by increasing feed moisture while negative coefficients of screw speed and barrel temperature indicated that hardness

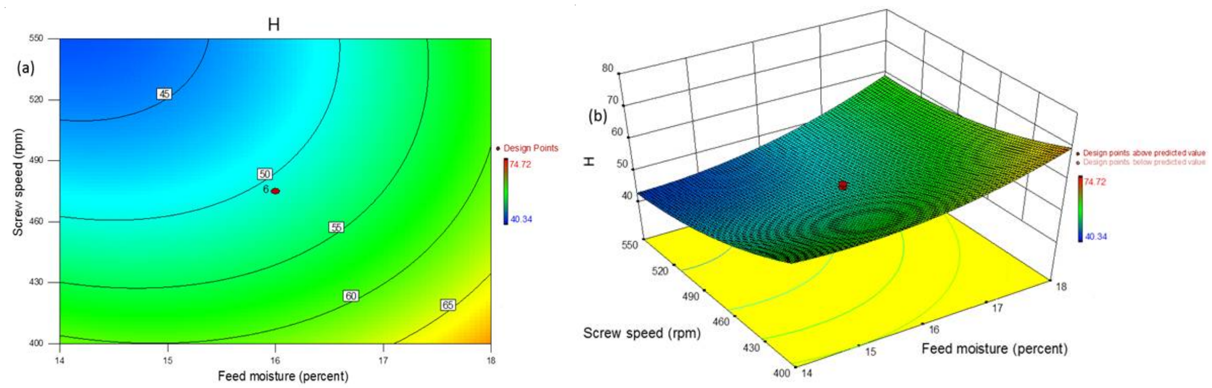

Figure 6: Contour (a) and Response surface (b) plot depicting the behavior of hardness at different feed moisture and screw speed while the other processing variables are at center point

decreased by increasing of these two variables. The interactions between feed moisture and screw speed; and screw speed and barrel temperature were found to have significant positive correlation with hardness (Figure 6). Hardness increased with increasing feed moisture because water acts as a plasticizer to the starch-based material reducing its viscosity and the mechanical energy dissipation in the extruder thus the product becomes dense and bubble growth gets compressed (Altan *et al.*, 2008). It was found that both of screw speed barrel temperature had inverse effect on hardness of extruded product. Increasing of these two variables may reduce the melt viscosity that improve bubble forming subsequently reducing density, reducing hardness and therefore increasing crispness of extrudates (Singh *et al.*, 2015).

3.7. Optimization

A graphical optimization technique of RSM software was used to determine the optimum combinations of feed moisture, screw speed and barrel temperature for processing of maize-fish flour based extrudates. Numerical optimization provided five solutions with desirability values varying from 0.56 to 0.93. Predicted values of ER (2.63-2.96), BD (0.21-0.24 g/cm^3), WAI (5.24 -5.61 Wh/kg), WSI (21.52-23.36%) and hardness (40.58-46.55 N) were used for overlay plot graphical optimization. Superimposing the individual contour plots for the product response variables resulted in the identification of a region (shown by the black area) that satisfied all constraints. The optimum extrusion conditions that can be used to produce extrudates with the estimated physical and textural characteristics were 14.27-15.12% feed moisture content, 400-463 rpm of screw speed and 173.61 °C of barrel temperature.

4. Conclusion

A significant effect of extrusion conditions (screw speed, feed moisture and barrel temperature) on physical properties of fish-maize based extruded snacks was clearly observed. To get the maximum ER, maximum WAI, minimum BD and minimum hardness; it is recommended to use a combination of extrusion conditions that includes 14.27-15.12% feed moisture content, 400-463 rpm of screw speed and 173.61 °C of barrel temperature. It was concluded that fish-maize based extruded snacks with high quality and nutritional value could be produced by using the said combination of extrusion conditions.

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