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Relationship Between Extrusion Conditions and System Parameters of Extrusion Cooking of Cassava and Soybean Blends: Application of Response Surface Analysis

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Abstract

Blends of cassava flour and partially defatted soybean four were processed in a single-screw extruder. Experimental design with feed moisture (FM)(16, 20, 24 gwater/100g flour), amount of soybean (10–30 gsoybean/100g flour) and barrel temperature (120, 145, 170 ^{o}C) as independent variables produced 17 different combinations that were studied using Box-Behnken Design of response surface methodology to investigate the effect of these variables on extruder system parameters, namely, product temperature (PT), residence time (RT), machine throughput (MT) and specific mechanical energy (SME). The recorded values for all responses varied from 121 to 175 ^{o}C, 42.34 to 65.11 seconds, 3.65 to 4.56 and 159.01 to 213.63kJ/kg, respectively. Second-order polynomials were used to model the extruder responses as a function of process variables. All three variables affected responses significantly especially their linear terms ($P<0.05$) and all the fitted models were all significant ($P<0.05$) and correlated with experimental data ($R^2 \geq 0.934$).

Keywords: Cassava flour, Soybean flour, Product temperature, Residence time, Machine throughput, Specific mechanical energy.

1 Introduction

Snacks and ready-to-eat cereals have become a part of the feeding habits of the majority of the world population because they provide convenient portions and fulfill short-term hunger (Tettweiler 1991; Kuntz, 1996). Extrusion cooking has been an effective technique in food process industry for production of these convenience foods of diverse attributes due to its high productivity rate, very high energy efficiency, no effluents generation, e.t.c. (Harper, 1981)

To produce snacks, starch is the main constituent and is responsible for most of their structural and/or expansion attributes. Many raw materials have been used to develop various types of snack foods. The basic component of investigation is starch and/or flour from cassava just like any other starchy food crops such as corn, wheat, rice and potato, which is the key component for the product structuring (Matthey and Hanna, 1997; Sun and Muthukumarappan, 2002; Singh *et al.*, 2007a; Anton *et al.*, 2009) and expansion. These snacks, however, tend to be high in calories and fat and low in proteins, vitamins, and other nutrients (Ranhotra and Vetter 1991) and therefore, are needed to be fortified by addition of proteinaceous food materials especially soybean for high quality and quantity of its protein similar to that of animals that will require a lower degree of cassava flour replacement to increase the nutritional contribution of expanded snacks and still help to keep consumer acceptance high.

Extrusion cooking being a multivariate process demands close control of many input variables such as feed moisture, feed composition, feed particle size, feed rate, barrel temperature, screw speed, screw configuration, and die geometry. These material and process variables determine the extent of macromolecular transformations during extrusion, which in turn ultimately influence the rheological properties of the food melt in the extruder and, consequently, the physical, functional and sensory characteristics of extrudates (Patil *et al*., 2007).

Despite increased use of extrusion technology, extrusion process is still a complicated multi-input–output system that is yet to be mastered (Chen et al., 2010). Efforts have been made to categorize extrusion parameters into three groups, namely, process parameters (including screw speed, moisture content, barrel temperature, screw configuration, die dimension, raw material characteristics etc.), system parameters (including energy input, residence time, product temperature, machine throughput, etc.), and products properties (including color, nutrition, texture, taste etc.) by a simplified system analysis model (Meuser and Van Lengerich, 1984). Among these three kinds of parameters, process parameters hold the key of correlating the other two parameters and not vice versa, it is thus imperative to investigate the effect of ingredient and process variables on these extruder system parameters. Process responses or extruder system correlates well with extrudate physical properties such as expansion, density and texture characteristics (Altan *et al*., 2008; Dogan and Karwe, 2003; Chen *et al., 2010*) that evaluate the consumer acceptability of the final product (Patil *et al*., 2007). These parameters are consequence of different combinations of extrusion conditions such as feed moisture, feed composition, barrel temperature, e.t.c (Moraru & Kokini, 2003).

The objective of this study was to investigate the effects of extrusion conditions, feed moisture (FM), amount of soybean (AS) and barrel temperature (BT), on product temperature (PT), residence time (RT), machine throughput (MT) and specific mechanical energy (SME) using response surface methodology.

2 Materials and Methods

2.1 Materials

A year old sweet local variety of cassava (*Manihot esculenta Crantz*) roots popularly known as Okoyawo among the local farmers and processors in Ogbomoso, Nigeria and its environs and soybean were sourced from the Teaching and Research Farms of the Ladoke Akintola University of Technology (LAUTECH), Ogbomoso, Nigeria and processed into flour as described by Badrie and Mellowes (1991). Whole soybean seeds were dried in an air convective cabinet drier at 50 ^{o}C until a moisture content of 7 % (w.b.) was reached. The dried beans were cracked between plates of attrition mill to separate the cotyledons and hulls which were then willowed off to remove the hulls. The clean cotyledons were thereafter milled and made to pass through 500 μm British standard sieve. The resulting soybean flour was defatted to 8.15 % final fat content from its original fat content of 18.35 % using hexane solvent. The partially defatted flour was dried in the oven at 50 ^{o}C for 24 h to dissolventise the residual hexane. Both the cassava and partially defatted soybean flour (CF and PDSF) were milled in a plate attrition mill to break up the clumps and made to pass through a 500 μm British standard sieve and packed separately in HDPE bags and kept under refrigeration in a freezer until further use. All chemicals used were of analytical grade.

2.2 Chemical composition of raw ingredients.

The chemical composition of the cassava flour and partially defatted soybean flour were analyzed for moisture, crude protein (N × 6.25), total fat, crud fiber and ash content using AOAC (1995) standard methods 925.10, 920.87, 920.39, 925.08 and 923.03 respectively. Carbohydrate content was determined by difference 100 − (% moisture + % protein + % fat + % ash). Atwater energy conversion factors 17 kJ/g (4 kcal/g), 37 kJ/g (9 kcal/g) and 17 kJ/g (4 kcal/g) were used to calculate the energy contribution of protein, fat and carbohydrate, respectively (AOAC, 2005). Chemical composition of raw material is shown in Table 1.

Table 1:Chemical composition of raw materials (g/100g)

Parameter	CF	PDSF
Moisture	9.00	7.33
Crude fat	0.27	8.15
Crude protein (N x 6.25)	1.95	46.11
Crude fibre	2.86	2.19
Ash	1.75	5.03
Carbohydrates(by difference)	84.17	31.19
Energy (kJ/g) (Atwater factor)	1569.74	1615.59

CF, Cassava flour; PDSF, partially defatted soybean flour.

2.3 Extrusion process

The extrusion cooking process was conducted in a simple local single-screw extruder (Nigerian design) with the following specifications and as shown in Table 2 (Abioye, 2016). The extruder has a barrel diameter of 32 mm, a length/diameter ratio of approximately 15:1, a nominal compression ratio of 2.2 and a die opening of 5 mm with L/D ratio of approximately 2:1. The inside of the barrel was grooved to ensure zero slip at the wall. The barrel was divided into four zones namely, feeding, compression, metering and pre-die sections. The feed end was cooled by water through a water jacketed cooling system to maintain the temperature below 65 ^{o}C while the compression section was neither cooled nor heated and the metering section was electrically heated without cooling to pre-determined temperatures according to experimental design (Table 3) using a thermostatic temperature control system. A vertical screw dispenser fed the extruder from the hopper at a volumetric flowrate of approximately 250 cm^{3}/min. The independent variables in the experiments were feed moisture (FM) of 16, 20 and 24 % (wb), amount of soybean (AS) of 10, 20 and 30 g /100 g flour) and barrel temperature (BT) i.e. temperature at the metering section of (120, 145, 170°C (Table 3 and 4). CF and PDSF were mixed adjusted to predetermined moisture content levels by addition of calculated amount of water that was sprayed and admixed into each sample w/w according to the experimental design (Table 3). Thereafter, each of the samples was sealed in HDPE bag and kept in refrigerator for 24 hours for equilibration and later brought out to room temperature for at least another 24 hours for the sample to attain room temperature. The moisture content of the blends was ascertained before extrusion by drying the samples to a constant weight in an air-convection oven at 105 ^{o}C (AOAC, 1995). All experiments were performed at screw speed of 150 rpm. Table 4 presents all the experimental runs of extrusion. Extrudates were cooled and dried at 50 °C for 2 days, packed in HDPE bags and stored in a refrigerator at 4°C until further analysis.

Table 2: Specifications of the developed extruder

Parameters	Dimension
Length of the barrel (L), mm	470.0
Length of the feed section, mm	110.0
Length of the compression section, mm	190.0
Length of the metering section, mm	130.0
Outer diameter of the barrel (D), mm	42.0
Inner diameter of the barrel (d_b), mm	32.0
Diameter of the screw(D_s), mm	31.0
Root diameter of the screw at the beginning of compression section (d_f), mm	15.0
Clearance between screw and barrel (δ), mm	0.5
Root diameter of the screw at the end of compression section (d_m), mm	25.0
Flight height in the feed section (H_f), mm	8.0
Flight height in the metering section, mm	3.0
Compression ratio (C.R.)	2.2
Die diameter, mm	4.0
Shear rate, s^{-1}	111.7
Screw speed, rpm	0 - 200
Channel width length (W), mm	27.63
Helix angle (θ), ^{o}	10
Theoretical mass flowrate, kg/hr	5
Specific mechanical energy, kW.hr/kg	0.1182

2.4. *Experimental design and statistical analysis*

The effect of feed moisture (FM), amount of soybean (AS) and barrel temperature (BT) on some system parameters of the extrusion cooking of cassava and soybean blends was investigated using a Box Behnken design (1960). The resulting experimental design included a total of 17 treatments with three levels of each factor with five replicates at the centre point to minimize the errors. Table 3 shows the levels the levels of feed moisture (x_1), amount of soybean (x_2) and barrel temperature (x_3) used in the experiments. From each experimental run the product temperature (PT), residence time (RT, machine throughput (MT) and specific mechanical energy (SME) were determined as the response variables (Tables 3 and 4). Finally, a second-order polynomial regression analysis was conducted using the Design Expert 6.0 (State-Ease Inc., Minneapolis, MN, USA) to relate each response with the FM, AS and BT by using the following response surface model with main, interaction, and quadratic terms:

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{23} x_2 x_3 + \beta_{11} x_1^2 + \beta_{22} x^2 + \beta_{33} x_3^2 \quad \textbf{(1)}$$

Table 3: Process variables and their levels

Process variable	Symbol		Level		
	Original	Coded	-1	0	+1
Feed moisture (g water/100g)	FM	x_1	16	20	24
Amount of soybean (g soya/100g)	AS	x_2	10	20	30
Barrel temperature (^{o}C)	BT	x_3	120	145	170

The significance of the model was tested by an analysis of variance (F-test, $p \leq 0.1$, 0.05 and 0.01). Student's t-Test was used for the determination of the significance of the individual effects for each of the coefficient estimates. The non-significant terms ($p \geq 0.05$) were withdrawn from the model, and a new adjustment made so that only significant terms were included in the final model. Using the multiple regression equation as starting point, surface response analysis curves were elaborated within the intervals studied (Montgomery, 2005).

2.4 *Determination of extrusion system parameters*

2.4.1 *Product temperature (PT)*

Product temperature (^{o}C) was read out from the analogue thermocouple during extrusion runs on emerging extrudates at the die end of the extruder. Samples were collected in an adequately insulated and closed receiving vessel. A minimum of five readings were taken and averaged for each sample run (Iwe, 1997).

2.4.2. *Residence time (RT)*

RT or breakthrough time was determined according to the method described by van Zuilichem (1992) and modified by Oke *et al*. (2013). A food grade colour was introduced at the feeding port and the time taken for the colour to first show up at the die was taken as the residence time.

2.4.3 Machine throughput (MT)

MT (kg/h) (or mass flow rate) was determined when steady state operation conditions were reached as indicated by constant amperage and constant barrel temperature. Extrudate flowing out of the extruder die orifice was collected as soon as the stopwatch was started at 60 seconds intervals. The mean weight of 5 such collections was calculated for each run as the mass flow rate for that run in kilogram per hour (Nwabueze and Iwe, 2006).

2.4.4 Specific mechanical energy (SME)

SME, the net mechanical energy input (after no-load correction) divided by mass flow rate, provides a good characterization of the extrusion operations. SME input was calculated with a modification according to the method described by Su (2007). Specific mechanical energy (SME) (kJ/kg) was determined based on the ratio of power consumption (Watts) to MT (kg/s) (Iwe, 1997) using equation 2.

$$SME = \frac{\sqrt{3} * \left(I_f - I_e\right) * V_L * \cos\alpha * N}{\dot{m} * N_{\max}} \qquad 2$$

where,

I_e = current amperage reading from frequency inverterwhen running empty, A

I_f = current amperage reading from frequency inverter when running fully loaded, A

V_L = voltage reading from voltmeter, volts

$\cos\alpha$ = motor (power) factor = 0.85

N = screw speed, r.p.m.

N_{max} = maximum screw speed, r.p.m.

$\dot{m}$ = machine throughput, kg/s

Amperage (I_f) was recorded every 30 s until when constant data point was achieved for each processing condition.

3 Results and Discussion

3.1 Diagnostic checking of fitted model and surface plots for various responses

Table 4 summarizes the overall results of responses of the extrusion cooking of cassava and soybean blend samples at different levels of input variables using a single-screw extruder. These system parameters such as product temperature (PT), residence time (RT), machine throughput (MT), specific mechanical energy (SME), e.t.c. are a measure of system technical performance and have significant effects on macromolecular degradation of biopolymers (Lazou and Krokida, 2010). As they result from different combinations of extrusion conditions such as feed moisture, amount of soybean, screw speed and barrel temperature. System parameters can be used to describe or compare the extrusion process under different operating conditions (Kokini and Moraru, 2003). It has been shown that SME correlates well with extrudate properties such as expansion, density and texture characteristics (Onwulata *et al*., 2001; Dogan and Karwe, 2003; Altan *et al*., 2009).

The significance of coefficients of fitted quadratic model for all responses (Eq. (4 - 8) was evaluated by using the F-test and P-value.

3.1.1 Product temperature, Y_{PT}

All input variables had highly significant negative linear effect on PT except BT (x_3) that had positive linear effect ($P < 0.01$), FM had quadratic effect ($P < 0.05$) on the PT. The interaction of AS and BT (x_2x_3) had significant (negative) effect ($P < 0.05$) on PT, so that high values of PT were found at low level of AS, dependent on BT (Figure 1). The analysis of variance (ANOVA) for PT of quadratic model (equation (5) is given in Table 4. Regression model fitted to experimental results of PT showed good correlation coefficient ($R^2 = 0.999$). Table 5 shows that the F-value for PT was very significant ($P < 0.05$) and lack-of-fit was not significant ($P > 0.05$) relative to the pure error, indicating that the second-order polynomial model correlated well with the measured data. Therefore, the model can be used to navigate the design space.The resulting polynomial after removal of non-significant ($p \geq 0.05$) terms is given in equation 3:

$$Y_{PT} = 146.20 - 1.87x_1 - 1.50x_2 + 24.88x_3 - 1.75x_2x_3 + 1.65x_3^2 \qquad 3$$

The significant quadratic effect of barrel temperature was reflected on response surface plot (Figure 1) with a curved surface. It was also observed on the response surface plot (Figure 1) that increased BT led to a significant increase of PT at low level of FM and AS and increase in AS had no significant effect on PT. Among the three variables, AS had the least effect on PT.

The measured PT values in extrusion cooking of cassava and soybean blends ranged from 121 to 175°C as shown in Table 4. It was expected that PT would be higher than the barrel temperature because more heat was generated just behind the die due to further resistance to melt flow and consequently higher temperature of extrudates. PT increased with increasing temperature and decreasing FM and AS. This could be attributed to the fact that low moisture content of feed ingredients restricted material flow inside the extruder barrel and at the die, increasing the shear rate and residence time, which will in turn increase the PT. Similar reports have been made about rising product temperature in the extrusion of starchy materials (Jin *et al*., 1994; Meng *et al*., 2010). Product temperature or melt temperature plays an important role in changing the rheological properties of extruded melts, which in turn affect the degree of expansion (Meng *et al*., 2010). Water acts as a plasticizer in the extruder, and increasing FM reduces melt viscosity and mechanical energy dissipation (Ilo *et al*., 1996) and thus, product temperature was lower. Also, the presence of oil in the feed material reduced friction between extruder barrel and screw walls and thus, reduced the product temperature.

Table 4: Effects of extrusion conditions on some system parameters[a]

Run No.	Independent variables			Response/dependent variables[d]			
	FM (x_1)	AS (x_2)	BT (x_3)	Y_{PT}	Y_{RT}	Y_{MT}	Y_{SME}
1	16(-1)	10(-1)	145(0)	150	49.67	4.51	193.23
2	24(+1)	10(-1)	145(0)	147	57.18	3.88	191.47
3	16(-1)	30(+1)	145(0)	147	43.25	4.39	187.44
4	24(+1)	30(+1)	145(0)	145	57.85	3.65	159.01
5	16(-1)	20(0)	120(-1)	127	45.19	4.62	211.07
6	24(+1)	20(0)	120(-1)	121	55.73	4.10	211.56
7	16(-1)	20(0)	170(+1)	175	62.12	4.01	172.78
8	24(+1)	20(0)	170(+1)	171	65.11	3.86	164.23
9	20(0)	10(-1)	120(-1)	121	42.34	4.56	213.17
10	20(0)	30(+1)	120(-1)	121	46.21	4.44	213.63
11	20(0)	10(-1)	170(+1)	175	56.24	3.96	181.98
12	20(0)	30(+1)	170(+1)	168	53.12	3.79	169.93
13	20(0)	20(0)	145(0)	145	50.55	4.10	203.75
14	20(0)	20(0)	145(0)	146	48.94	4.15	200.32
15	20(0)	20(0)	145(0)	147	52.67	4.11	202.35
16	20(0)	20(0)	145(0)	147	49.28	4.09	206.11
17	20(0)	20(0)	145(0)	146	50.26	4.11	203.59

[a] Box and Behnken with three levels and three factors, 17 experiments.

[b] Does not necessarily corresponded to the order of experiment.

[c] FM, feed moisture (g water/100g); AS, amount of soybean (g soyabean/100g); BT = barrel temperature (°C). Values in parentheses are the coded levels.

[d] Y_{PT}, product temperature (°C); Y_{RT}, residence time (seconds); Y_{MT}, machine throughput (kg/h); Y_{SME}, specific mechanical energy (kJ/kg).

3.1.2 Residence time, Y_{RT}

RT of CSE was significantly affected by positive linear terms of FM (x_1) and BT (x_2) at $P < 0.05$. FM and AS had significant quadratic effects ($P < 0.05$) on RT of extrudates. All the interaction terms were not significant ($P > 0.1$). Regression model (equation 6) fitted to experimental results of RT showed higher coefficient of determination ($R^2 = 0.967$). RT model (equation 4) was significant ($P<0.01$) with a insignificant lack-of-fit ($P>0.05$), hence, the model can be used to navigate the design space. The resulting polynomial after removal of non-significant ($p \geq 0.05$) terms is as given in equation 4:

$$Y_{RT} = 50.34 + 4.47x_1 + 5.89x_3 + 4.62x_1^2 - 2.94x_2^2 \qquad 4$$

As expected, the higher the proportion of cassava (indicative of increase in starch content), the higher the viscous nature of the mixture and the more the difficulty of exit of the extrudate from the die (Iwe *et al*., 2001). It was observed on the response surface plot (Figure 2) that increased FM and BT led to a significant increase of RT, this could be attributed to the fact that higher barrel temperature and moisture were important factors that favor increment in the extent of gelatinization which in turn might increase the viscosity of the melt thereby offering increased resistance to flow in the barrel and consequently increase in the RT. RT is one of the system parameters that link the input variables (such as feed moisture, amount of soybean, barrel temperature, e.t.c.) to product parameters (such as expansion ratio, density, water absorption index, texture, e.t.c.).

It determines the extent of chemical reactions and ultimately the quality of the extruded products (Gogoi and Yam 1994). It represents the time the material is exposed to heat, shear and allows chemical reactions to take place within the extruder barrel (Rodríguez-Miranda *et al*., 2012). The residence time (RT) of CSEs obtained from the extrusion system ranged from 42.34 to 65.11s (Table 4). This incidentally falls within the range of values reported by Colonna *et al*. (1989) and van Zuilichem (1992) ,Iwe *et al*. (2001) in literature reported for mean residence time of starchy materials in a single-screw extruder.

Table 5: Regression coefficients and analyses of variance of second-order polynomial models showing relationships among system parameters and process variables.

Coefficient	Product temperature, Y_{PT}	Residence time, Y_{RT}	Machine Throughput, Y_{TP}	Specific mechanical energy, Y_{SME}
Intercept				
β_0	146.20***	50.34***	4.11***	203.22***
Linear				
β_1	-1.87***	4.47***	-0.26***	-4.78***
β_2	-1.50***	-0.69^{+}	-0.08*	-8.48***
β_3	24.88***	5.89***	-0.26***	-22.32***
Quadratic				
β_{11}	1.65**	4.62***	-0.022^{+}	-14.85***
β_{22}	-0.60^{+}	-2.94**	0.018^{+}	-5.58**
β_{33}	0.65^{+}	2.08*	0.058^{+}	1.54^{+}
Interactions				
β_{12}	0.25^{+}	1.65^{+}	-0.027^{+}	-6.67***
β_{13}	0.50^{+}	-1.89^{+}	0.093*	-2.26^{+}
β_{23}	-1.75**	-1.75^{+}	-0.013^{+}	1.37^{+}
Test of model adequacy				
R^2	0.999	0.967	0.934	0.985
$p \leq$	0.0001	0.0006	0.0023	0.0001
p value for model lack-of-fit	0.2234	0.1575	0.0011	0.0622

* significant at $p < 0.1$ level; ** significant at $p < 0.05$ level; *** significant at $p < 0.01$ level.
$^{+}$ not significant.

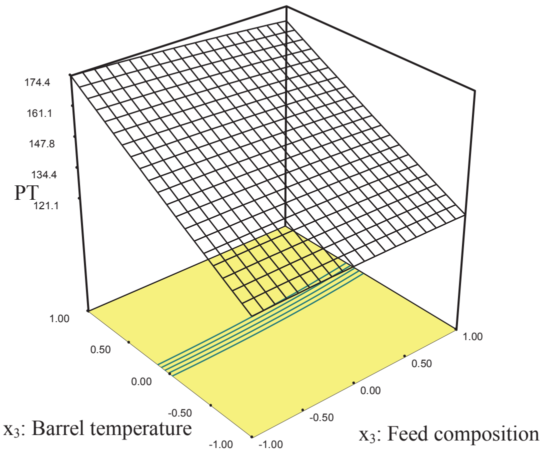

Figure 1: Response surface for the effect of input variables and their interactions on product temperature of extrudates.

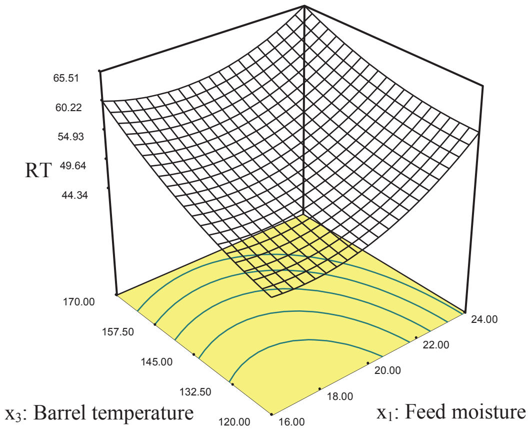

Figure 2: Response surface for the effect of input variables and their interactions on residence time of extrudates.

3.1.3 *Machine throughput (MT)*

Recorded values of the rate of exit of extrudates from the die (i.e. MT) are presented in Table 4. Analysis of variance showed that there were significant linear effects of all the independent variables on MT of the machine with FM and BT having high influence ($p < 0.001$) and to a lesser extent the AS ($p < 0.1$). The independent variables had no quadratic and cross-product effects on MT ($p > 0.1$) as shown on Table 5.

, with a coefficient of determination (R^2) which is high (at 0.934). RT model was very significant ($P < 0.05$) whereas lack-of-fit was also significant ($P > 0.05$). The results showed that the model fitted the linear regression model. Removing the non-significant terms, the model polynomial became equation 5:

$$Y_{MT} = 4.11 - 0.26x_1 - 0.080x_2 - 0.26x_3 \qquad 5$$

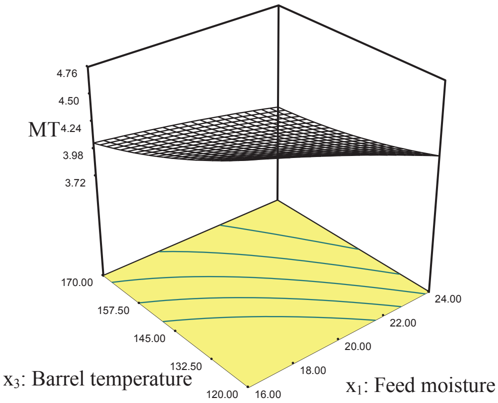

Figure 3: Response surface for the effect of input variables and their interactions on machine throughput of extrudates.

Relationships (Equation 5) between the independent variables and the dependent variable (MT) showed that increasing moisture of feedstock and BT caused a decrease of MT (Figure 3). Chevanan *et al*. (2008) .and Oke, *et al*. (2013) reported similar findings. This effect could probably be attributed to an increase in backflow due to reduced viscosity which the increase in moisture induced (Senanayake and Clarke, 1999).

3.1.4 *Specific mechanical energy, Y_{SME}*

Specific mechanical energy (SME) encompasses extruder system parameters such as screw speed, amperage/torque and MT in its determination i.e. equation 2. The experimental values for SME for CSEs are as resented in Table 4 and showed that all independent variables have significant ($p < 0.05$) negative linear effects on SME. There was significant ($p < 0.05$) interaction effect of FM and AS on SME. But there were no significant ($p < 0.05$) cross product effects of FM and BT and AS and BT on energy demand of the extruder as expressed in SME. The model developed from regression analysis of the results accounted for 96.5% of the total variation in SME and exhibited no significant ($p > 0.05$) lack-of-fit. The second-order polynomial equation for SME resulting after the removal of non-significant terms is as given in equation 6:

$$Y_{SME} = 203.22 - 4.78x_1 - 8.48x_2 - 22.32x_3 - 6.67x_1x_2 - 14.85x_1^2 - 5.58x_2^2 \qquad 6$$

As expected, SME decreased with FM, AS and barrel temperature (Table 4 and Figure 4). Calculated SME values ranged from 159.01 to 213.63 kJ/kg (Table 4). High SME was observed at low BT, low FM and barrel temperature and low SME was recorded at high temperature in Table 4 and, the response surface plot (Figure 4). The response surface plots of these effects on SME are as shown in Figure 4. Analysis of the responses showed a curved shape with quadratic effects of all the variables being pronounced as indicated in equation 6. Increasing the BT indicates that the energy supplied to the product in the extruder by the electric heater mounted on the barrel increased thereby reducing the viscosity of the melt which in turn reduced viscous dissipation of heat by friction between the barrel wall and the rotating screw channels and thus, gave rise to low energy consumption that manifested as SME. Lower SME values recorded for other combination of variables could be explained on the basis of feed lipid and moisture contents of the formulations, which played significant roles on friction in the extrusion process. Low moisture feeds have higher frictional resistance and draw higher power than high moisture feeds do. As Nwabueze and Iwe (2007) reported, the lubrication effect of fat at higher soybean inclusion in the blends coupled with increase in FM proved to be more significant in reducing torque than the effect of increasing breadfruit as a starch source. This explanation could be strengthened by the fact that energy required to turn the extruder screw is related to viscosity of the food material in the screw channel (Harper 1989). At low BT and FM, the need for more mechanical power to overcome resistance offered by the material coupled with the expected higher die pressure of extrusion would lead to a higher overall power requirement.

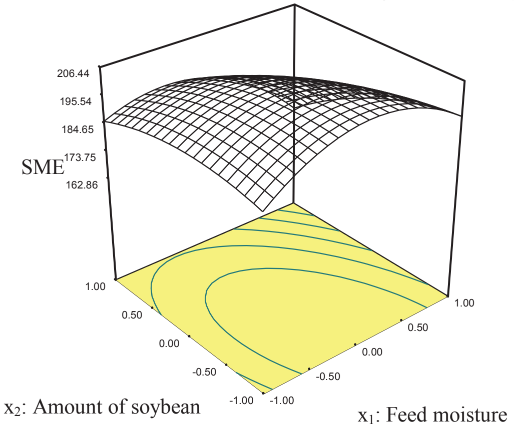

Figure 4: Response surface for the effect of input variables and their interactions on specific mechanical energy of extrudates.

4 Conclusions

Regression equations describing the effect of each variable on the system parameters and product responses were obtained. All the system parameters were linearly dependent on all input variables at P<0.01 except AS on RT and MT at P>0.1 and P<0.1, respectively.FM had higher quadratic influence on all the responses except MT (p<0.05) while AS and BT had quadratic influence on RT and SME (P<0.05) and RT (P<0.1) respectively. Combinations of FM and AS, FM and BT, and AS and BT had significant effects on SME, RT and PT at P<0.01, P<0.1 and 0.05, respectively. All the models for response were significant at P<0.05 with insignificant lack-of-fit (P>0.05) except MT (P<0.05), however, they all exhibited good correlation with experimental values with R^2 values ≥ 0.934, therefore, the models after removing non-significant terms (P>0.05) can be used to navigate the design space.

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