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Relationships 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 meal were processed in a single-screw extruder. Experimental design with feed moisture (16, 20, 24 gwater/100g flour), amount of soybean (10, 20, 30 gsoybean/100g flour) and barrel temperature (120, 145, 170 ^{o}C) as independent variables leading to 17 combinations that were studied using Box-Behnken Design of response surface methodology to investigate the effect of these input variables on extruder system parameters, namely: product temperature, residence time, machine throughput and specific mechanical energy. The recorded values for all responses varied from 121 to 175 ^{o}C, 42.34 to 65.11 seconds, 3.65 to 4.56 kg/hr and 159.01 to 213.63 kJ/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 significant ($p<0.05$) and correlated well with experimental data ($R^2 \geq 0.934$).

1. Introduction

Snacks and ready-to-eat cereals have become a part of the feeding habits of a majority of the world population because they provide convenient portions and fulfill short-term hunger [1,2]. Extrusion cooking has been an effective technique in the food process industry for the production of these convenience foods of diverse attributes due to its high productivity, very high energy efficiency and no effluent generation [3].

To produce snacks, starch from cassava just like any other starchy food crop such as corn, wheat, rice and potato, is the main constituent responsible for most of their structural and/or expansion attributes. [4]. These snacks tend to be high in calories and low in proteins, vitamins, and other nutrients [1] and therefore, need to be fortified with the addition of proteinaceous food materials e.g. soybean for high quality and quantity of its protein analogous to that of animals that will require a lower degree of cassava flour replacement to increase the nutritional quality of expanded snacks and still help to keep consumer acceptance high [5].

Extrusion cooking is a multivariate process that demands close control of many input variables [6] which determine the extent of macromolecular transformation, rheological and, ultimately, the physical, functional and sensory characteristics of the extrudates [6,7]. Despite expanding use of extrusion technology, the extrusion process is still a complicated multi-input–output system that is yet to be fully mastered [8].

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 product properties (including color, nutrition, texture, taste, etc.) that can lead to a simplified system analysis model [9].

Among these three kinds of parameters, process parameters hold the key to correlating the other two groups of 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 of the extruder system correlate well with extrudate physical properties such as expansion, density and textural characteristics [8,10,11] that define consumer acceptability of the final product [7]. These parameters result from varying combinations of extrusion conditions such as feed moisture, feed composition, barrel temperature, etc. [12].

The Response surface methodology (RSM) is defined as the statistical method that uses quantitative data from an appropriate experimental design to determine and simultaneously solve multivariate equations. The main advantage of the RSM is that it reduces the number of experiments needed to evaluate multiple parameters and their interactions [13]. The RSM has been successfully applied for optimizing conditions in food research [8,13,14,15,16,17,18,19,20]. The purpose of our study was to investigate the effects of extrusion conditions which include feed moisture (FM), amount of soybean (AS) and barrel temperature (BT) on system parameters such as product temperature (PT), residence time (RT), machine

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throughput (MT) and specific mechanical energy (SME) using RSM.

2. Materials and Methods

2.1 Materials

12-month old cassava roots (Manihot esculentu Crantz) of local variety Okoyawo as popularly called among farmers and processors in Ogbomoso, Nigeria and its environs were processed with modifications into flour (CF) within 24 hours after harvest according to Badrie and Mellowes [21]. Soybean seeds were processed into partially defatted soybean flour (PDSF) as described by Abioye *et al.* [6]. The proximate composition of the CF and PDSF were determined by procedures of AOAC [22]. Total carbohydrate was determined by difference. All chemicals were of analytical grade.

2.2 Extrusion process

Extrusion was performed on a low-capacity single-screw extrusion facility (Nigerian Design) with the following specifications [6]: The screw was of increasing root diameter and constant pitch with a compression ratio (channel depth in feed zone to that of metering zone) of approximately 2.2:1. The barrel diameter and its length to diameter ratio (L/D) were 32 mm and 15:1, respectively and a die opening of 5 mm with L/D ratio of approximately 2:1. The extruder barrel consisted of 4 zones, with last two zones heated by band electric heaters of 500-W each. The zone at the feed end was cooled by water while the other zone was neither cooled nor heated. The metering section was electrically heated to temperatures according to the experimental design (Table 1) using a temperature control system. A vertical volumetric screw feeder was improvised to force-feed the extruder at approximately 250 cm^3/min corresponding to speed of 150 rpm.

Table 1. Process variables and their levels

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

2.3 Experimental design and statistical analysis

The independent variables studied were feed moisture, FM (x_1) in gwater/100g, amount of soybean, AS (x_2) in gsoybean/100 g and barrel temperature, FM (x_3) in ^oC. The dependent variables or responses were product temperature, PT (Y_1) in ^oC; residence time, RT (Y_2) in s; machine throughput, MT (Y_3) in kg/h and specific mechanical energy, SME (Y_4) in kJ/kg were determined on the cassava soybean extrudates.

The experimental data were analyzed using multiple regression analysis using Design Expert 6.0 [23] to fit a second order polynomial model expressed in coded variables:

$$\underset{i=1}{\overset{4}{Y}} = \beta_0 + \sum_{i=1}^{3}\beta_i x_i + \sum_{i=1}^{3}\beta_i x^2{}_i + \sum_{i=1}^{2}\sum_{j=i+1}^{3}\beta_{ij} x_i x_j + \varepsilon \qquad (1)$$

where Y_i is the response (PT, RT, MT and SME), x_i and x_j are the independent variables (FM, AS and BT) in coded values and β_0, β_i, β_{ii} and β_{ij} are the regression coefficients of the model for constant, linear, quadratic and interactions terms, respectively. The effects of independent variables (FM, AS and BT) on the selected system parameters of the extrusion cooking of CSE blends were carried out applying Box Behnken design [24]. Table 2 shows the resultant experimental design that comprises of total of 17 treatments with three levels of each factor and five replicates at the centre point to minimize errors as adopted in earlier study [6]. The significance of the model was tested by the analysis of variance. The final models included only significant term ($p<0.1$) after discarding non-significant term ($p>0.1$) and response surfaces were plotted within the domain investigated as described by Chang *et al.* [25].

2.3 Determination of extrusion system parameters

2.3.1 Product temperature (PT)

PT($^{\circ}C$) was read out from analogue display of temperature controller 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 in accordance to Iwe *et al.* [26].

2.3.2 Residence time (RT)

RT or breakthrough time was determined according to the method described by Iwe *et al.* [26] with modifications. 1 g of food grade red color was introduced through a hole on the screw feeder flange into the feeding port and the time taken for the color to first show up at the die was taken as the residence time.

2.3.3 Machine throughput (MT)

MT (kg/h) (or mass flow rate) was determined as the kilogram of extrudates flowing out at the die per 60 s at steady state of operation as indicated by constant amperage and barrel temperature. The mean weight of 5 such collections was calculated for each run as the mass flow rate for that run in kilogram per hour [27].

2.3.4 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 operation [11]. SME input was calculated with modification according to the method described by Su [28]. Specific mechanical energy (SME) (kJ/kg) was determined based on the ratio of power consumption (Watts) to MT in kg/s [29] using Eq. 2.

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

where,

I_e = current amperage reading from frequency inverter when 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

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

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

3. Results and Discussion

The chemical composition of CF and PDSF were (%) respectively; moisture, 9.00 and 7.33; crude protein, 1.95 and 46.11; crude fat, 0.27 and 8.15; crude fiber, 2.86 and 2.19; ash, 1.75 and 5.03 and total carbohydrates 84.17 and 31.19.

Table 2 summarizes the overall results of responses of extrusion cooking of cassava and soybean blend samples at different levels of input variables using a single-screw extruder. Responses such as PT, RT, MT and SME are measures of system technical performance and reveal macromolecular degradation of biopolymer matrices in extrudates [30]. System parameters, being consequences of different combinations of extrusion processing conditions can be used to determine similarity and difference in extrusion process under these operating conditions [10,18].

Table 2. Effects of extrusion conditions on selected system parameters[a]

Run No[b].	Independent variables[c]			Response/dependent variables[d]			
	FM (x_1)	**AS (x_2)**	**BT (x_3)**	***PT (Y_1)***	***RT(Y_2)***	***MT(Y_3)***	***SME(Y_4)***
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 correspond to the order of the 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_1, product temperature (°C); Y_2, residence time (seconds); Y_3, machine throughput (kg/h); Y_4 specific mechanical energy (kJ/kg).

Table 3. Regression coefficients of second-order polynomial models

Coefficient	**PT (Y_1)**	**RT (Y_2)**	**MT (Y_3)**	**SME (Y_4)**
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.

3.1 Product temperature, Y_1

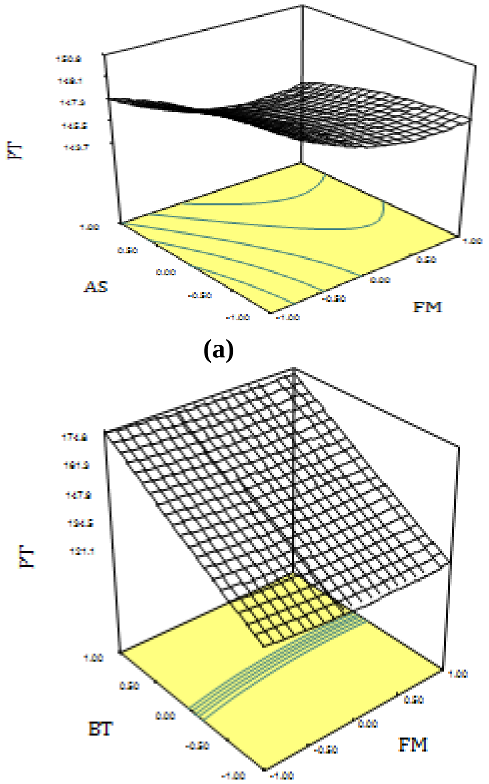
All input variables manifested high significant negative linear influences ($p < 0.01$) on PT except BT (x_3) which had high significant positive linear influence ($p < 0.01$); FM (x_1) had a quadratic effect ($p < 0.05$) on the PT. The interaction of AS and BT (x_2x_3) had a significant (negative) effect ($p < 0.05$) on PT, so that high values of PT were found at low levels of AS and dependent on BT (Fig. 1). Analysis of variance (ANOVA) for quadratic model of PT (Eq. 5) is as recorded in Table 3. The regression model fitted to the experimental values of PT showed a good coefficient of determination ($R^2 = 0.999$). Table 3 also shows that the F-value for PT was very significant ($p< 0.0001$) and non-significant lack-of-fit ($p> 0.05$) relative to the pure error, indicating that the regression equation correlated well with the experimental data within design space. The resultant polynomial with only significant ($p \geq 0.1$) terms is as follows:

$$Y_1 = 146.20 - 1.87x_1 - 1.50x_2 + 24.88x_3 - 1.75x_2x_3 + 1.65x_3^2 \quad (3)$$

The response surface plot shows the significant effect of BT on PT (Fig. 1) at low levels of FM and AS with a distinct curved surface and that increase in AS had no significant effect on PT. Among the three variables, AS had the least effect on PT.

The PT measured values in extrusion cooking of cassava and soybean blends ranged from 121 to 175°C as shown in Table 2. It was expected that PT would be higher than BT because more heat was generated just behind the die due to increasing resistance to melt flow and, consequently, higher temperature of extrudates. PT increased with increasing temperature and decreasing FM and AS. The high temperature at the die can be adduced to the low FM which restricts material flow in the barrel and at the die [31] as a result of increased shear and residence time [32]. Similar reports have been made about rising product temperature in the extrusion of starchy materials [18,33].

Majumdar and Singh [34] reported that BT temperature plays an important role in changing the rheological properties of melt and hence, the degree of expansion of extruded product. Decrease in PT was as a result of increase in FM which reduces melt viscosity and dissipation of mechanical energy in the extruder [34]. Also, the lubricating effect of oil in the feed material reduced friction between extruder barrel and screw walls and thus, reduced the product temperature.



(a)

(b)

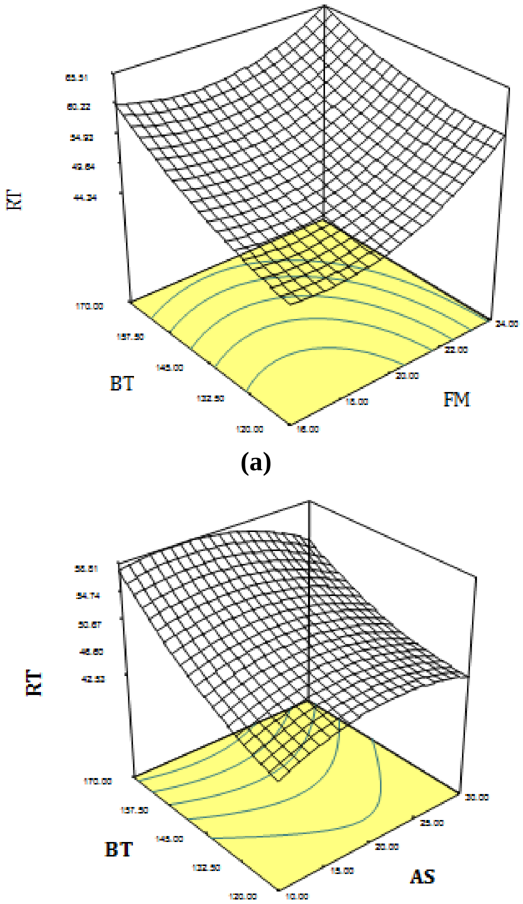
Figure 1. Response surface for the effect of input variables and their interactions on product temperature of extrudates

3.2Residence time, Y_2

RT of CSEs was significantly affected by positive linear terms of FM (x_1) and BT (x_2) at $p < 0.05$ and 0.01. FM and AS had significant quadratic effects ($p < 0.05$) on RT of the extrudates. All interaction terms were not significant ($p > 0.1$). The regression model (Eq. 6) fitted to the experimental results of RT showed a high correlation coefficient ($R^2 = 0.967$). The RT model (Eq. 4) was significant ($p<0.001$) with 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 ($p \geq 0.1$) terms, is as given in Eq. 4:

$$Y_2 = 50.34 + 4.47x_1 + 5.89x_3 + 4.62x_1^2 - 2.94x_2^2 + 2.08x_3^2 \tag{4}$$

As expected, the higher the amount of starch content of the feed ingredient, the more viscous the dough becomes in the barrel and the more the difficulty of exit at the die [26]. It was observed on the response surface plot (Fig. 2) that increased FM and BT led to a significant increase of RT. This could be attributed to the fact that higher BT and moisture were important factors that promoted gelatinization which, in turn, might increase the viscosity of the melt thereby offering increased resistance to flow in the barrel and inducing increase in the RT. RT is one of the system parameters that link the input variables (such as FM, AS, BT, etc.) to product parameters (such as expansion ratio, density, water absorption index, texture, etc.).



(a)

(b)

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

It determines the extent of chemical interactions and the quality of the extruded product [35]. It is the time the feedstock material is subject to heat and shear environment in the extruder allowing chemical reactions to take place [36]. RT of CSEs obtained from the extrusion system ranged from 42.34 to 65.11s (Table 2). This incidentally falls within the range of values reported by Colonna *et al.* [37], van Zuilichem [38] and Nwabueze and Iwe [39] in literature reports for mean residence time of starchy materials in a single-screw extruder.

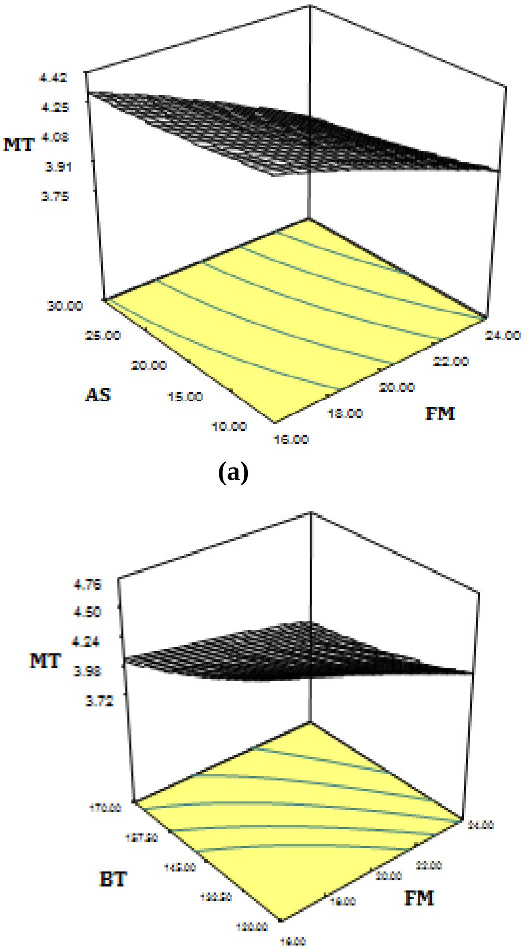
3.3 Machine throughput, Y_3

Recorded values of the rate of exit of extrudates from the die (i.e. MT) are as shown in Table 2. Analysis of variance (Table 3) showed that there were significant linear effects of all the input variables on MT of the machine with FM and BT having high influences ($p < 0.01$) and AS a lesser influence ($p < 0.1$). The independent variables had no quadratic and cross-product effects on MT ($p > 0.1$) as shown in Table 3, with a correlation coefficient (R^2) which is high (at 0.934). The RT model was very significant ($p < 0.001$), whereas its lack-of-fit was also significant ($p< 0.05$). The results show that the model fitted the linear regression model well. On removing the non-significant terms ($p>0.1$), the model polynomial became Eq. 5:

$$Y_3 = 4.11 - 0.26x_1 - 0.080x_2 - 0.26x_3 + 0.093x_1x_3 \tag{5}$$

Relationship (Eq. 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*. [40] and Oke *et al*. [19] reported similar findings. This effect could probably be attributed to an increase in the backflow due to reduced viscosity, which was induced by increase in moisture [41].



(a)

(b)

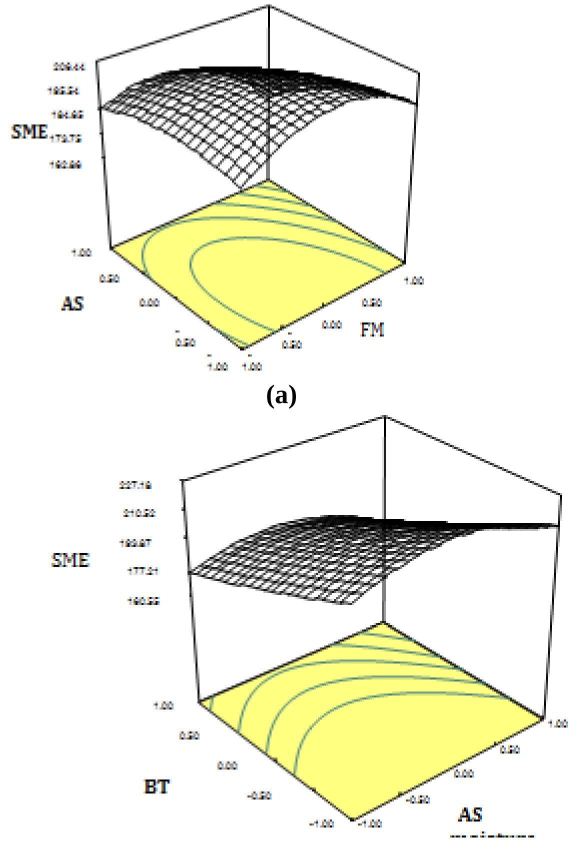
Figure 3. Response surface for the effect of input variables and their interactions on machine throughput

3.4 Specific mechanical energy, Y_4

Specific mechanical energy (SME) encompasses extruder system parameters such as screw speed, amperage/torque and MT in its determination (i.e. Eq. 2). The experimental values of SME for CSEs are as presented in Table 2. Table 3 showed that all independent variables have negative linear effects ($p < 0.05$) on SME. There was significant ($p < 0.05$) interaction effect of FM and AS on SME. But interaction effects of FM and BT and AS and BT on energy demand of the extruder as expressed in the SME values recorded were not significant ($p > 0.1$). The model developed from regression analysis of the results accounted for 96.5% of the total variation in SME and exhibited no ($p > 0.05$) lack-of-fit. The empirical equation for SME resulting after the removal of non-significant terms is as given in Eq. 6:

$$Y_4 = 203.22 - 4.78x_1 - 8.48x_2 - 22.32x_3 - 6.67x_1x_2 - 14.85x_1^2 - 5.58x_2^2 \quad (6)$$

As expected, SME decreased with FM, AS and BT (Table 2 and Fig. 4). Calculated SME values ranged from 159.01 to 213.63 kJ/kg (Table 2). High SME was observed at low BT low FM and BT and low SME was recorded at high temperature in Table 2 and the response surface plot (Fig. 4). The surface plots of these effects on SME are as shown in Fig. 4. Analysis of the responses showed a curved shape with quadratic effects of all the variables being pronounced as indicated in Eq. 6.



(a)

(b)

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

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, results in low energy consumption that manifested in SME. Lower SME values recorded for other combinations of variables could be explained on the basis of feed fat and moisture contents of the ingredients had significant lubricating effect in reducing the friction between the screw and barrel by reducing dough viscosity which a measure of resistance to flow of material and consequently, reduce energy (or torque) required to turn the screw [42,43]. At low BT and FM, the need for higher mechanical power to overcome the resistance offered by the material coupled with the expected higher die pressure of extrusion would lead to a higher overall power requirement.

4. Conclusion

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

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