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# Effect of Extrusion Cooking Variables on the Torque and Specific Mechanical Energy of a Single Screw Extruder

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***Authors' contributions***

*This work was carried out in collaboration between all authors. Author MOI designed the study. Author GCO carried out the dench work, performed the statistical analysis, wrote the protocol, the first draft of the manuscript and managed literature searches. All authors approved the final manuscript.*

***Original Research Article***

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## ABSTRACT

**Aims**: The operation of a single screw extruder under the influence of locally available raw materials (African yam bean (AYB) and cassava products were determined using the measures of torque and specific mechanical energy of the extruder. The specific mechanical energy (SME) is a good quantitative description in extrusion processes, since it allows the direct comparison of different combinations such as screw speed, feed rate and torque, while torque is directly correlated with power usage.
**Study Design**: A three- factor five level response surface methodology central composite design (CCD) was adopted to study the effect of feed moisture content (MC), feed composition (FC) and the screw speed (SS) on the energy efficiency of a single screw extruder using torque and specific mechanical energy (SME).
**Place and Duration of Study**: The raw materials for the work were obtained from Abia State Nigeria. The extrusion work was done at the Federal polytechnic Mubi Adamawa State Nigeria, while the statistical analysis was done at Michael Okpara University of Agriculture, Umudike Abia State Nigeria.
**Methodology**: African yam bean (AYB), cassava tubers and *Ighu* (pre-gelatinized

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cassava chips or slices) were processed into flours. The flours were sieved to pass 0.75mm laboratory mesh. The moisture content of the flours were determined. AYB flour was added to cassava flour at ratios of 0.54:99.46, 20:80, 50:50, 80:20 and 99.46:0.54. Also AYB was added to *ighu* flour in the same ratio as cassava flour. The moisture levels of the blends were adjusted by adding a pre-determined amount of water using material balance equation to yield (13.3, 16, 20, 24 and 26.7)% moisture content. The flour samples were then mixed and transferred into polythene bags and allowed to equilibrate for 12 hours at room temperature. Extrusion was carried out using a Brabender laboratory single screw extruder (Duisburg DCE -330 model). The screw speed was adjusted from 109.95 to 125,150,175 and 190.05rpm.Twenty extrusion runs were conducted with the cassava/AYB flour blends and another twenty extrusion runs were carried out for *Ighu/AYB* flour blends. Torque (T) was determined by reading directly from the extruder during extrusion run, while the specific mechanical energy was calculated from the data of torque and volumetric flow rate. Data obtained were subjected to response surface analysis (RSA) and analysis of variance (ANOVA).

**Results:** Regression analysis for extruded blends of *Ighu*/AYB showed that specific mechanical energy (SME) had significant ($p < 0.05$) linear, quadratic and interactive effects on the independent variables. Reduction in the moisture content of the feed materials resulted in an increase in the SME of the extruder. The result showed that the lowest torque occurred at the lowest moisture content and feed composition of AYB. The response surface plots showed that the maximum SME occurred at the critical values of screw speed and feed composition of 192.05 rpm and 0.54% *ighu*/ 99.46% AYB respectively. The responses obtained with cassava/AYB flour varied from the ones obtained using *ighu/AYB* blends, signifying that the feed composition had effect on the operation of the single screw extruder.

**Conclusion:** Extrusion variables influenced the torque and specific mechanical energy of the single screw extruder. The energy efficiency of the extruder was affected by the operating variables. The independent variables must be considered in the design of an experiment.

*Keywords: Torque; specific mechanical energy; single screw extruder; operating variables; response surface analysis.*

## ABBREVIATIONS

*SS: Screw Speed; MC: Moisture Content; FC: Feed Composition; AYB: AFRICAN Yam Bean; ighu = pre gelatinized cassava chips or slices; SME: Specific Mechanical Energy; T: Torque; CCD: Central Composite Design; RSA: Response Surface Analysis; M: Mass flow rate; Y = The response,* $X_1$ *= Screw speed,* $X_2$ *=Moisture content,* $X_3$ *= Feed composition,* $b_o$ *=intercepts, bi, b2,b3 are linear quadratic and* $b_{12}$, $b_{13}$ *and* $b_{23}$ *= interactions ;* $SME_{i=}$ *Specific Mechanical Energy of ighu/AYB;* $SME_c$ *=Specific Mechanical Energy of cassava/AYB;* $torque_{i=}$ *torque of ighu/AYB: Kg = kilogramme.*

## 1. INTRODUCTION

The use of extrusion cooking has allowed for both the development of new products and the increased utilization and stabilization of a wide range of raw materials [1]. A single screw extruder has a screw rotating in a closely fitting barrel. Transport of materials through single screw extruder, depends largely on friction at the barrel surface. Material flows forward (drag flow) owing to the action of the screw and, to a lesser extent backward, along the barrel (Pressure flow and leakage flow). Pressure flow is caused by the buildup of pressure behind the die and by material movement between the screw and the barrel. Single screw extruder operation depends on the pressure requirement of the die, the slip at the barrel wall (controlled by the barrel's wall temperature, the pressure of barrel wall grooves or both), and the degree at which the screw is filled [2]. The choice of the extruder depends on raw material and the desired end product [3]. To achieve optimum results in energy efficiency, extrusion productivity and product quality, it is necessary to determine proper combinations of operating variables such as feed composition, moisture content, operating temperature, screw speed, and die diameter. It is also good to investigate the impact of these variables on the capacity of the extruder [4].

Torque relates to the power consumption of the extruder and about 98% of the power input into the extruder is used for shearing and less than 1.5% is consumed in pumping [15].The torque required to turn the extrusion screw is related to its speed, fill and the viscosity of the food material in the screw channel [5]. Consequently, torque is an independent variable that provides some insight into the operation of the extruder. An increasing number of laboratory extruders have torque measuring capacity. The torque indicates that the resistive load on the extruder can be measured directly from the extruder. The effect of process variables on torque confirms the effect of these variables on product transformation (expansion and hardness).

Specific Mechanical Energy (SME) is the ratio of the net mechanical energy to the mass flow rate. In extrusion cooking, most of the energy from the extruder motor is used as friction which rapidly heats the food (between 50 and 100%) of the total energy input [5]. An overall energy balance on an extruder is important to account for energy flows and thermal energy added or removed in each zone. The energy balance enables calculation of the specific energy delivered (SED) to the product which is a good indicator of severity of treatment [6].

Central composite design (CCD) and response surface methodology (RSM) are the processes which combine mathematics with statistics in product optimization. In multifactor experiments, CCD and RSM can be used to comprehensively examine various parameters with minimum experimental times, and determine the most relevant factors. Extrusion of blends of cassava products and AYB flours is not a common practice. It is envisaged that acceptable, protein rich and ready to eat products will be produced from them. Such should lead to increased utilization of AYB and enrichment of cassava product. Moreover, response surface analysis can be seen to provide a quite effective means for the study and the optimization of operating conditions in extrusion technology. Investigating the effect of the operating variables on the productivity and energy efficiency of the extruder should be a welcome development.

## 2. MATERIALS AND METHODS

### 2.1 Sample Preparation

Cream coloured African yam bean (*Sphenostylis stenocarpa*) seeds (40 kg), were sorted/cleaned, soaked in water for six hours, dried, dehulled, milled, sieved and packaged. Cassava (Manihot exculenta, c) tubers (50kg) were peeled, washed, grated, dewatered, dried, milled, sieved and packaged. Pre-gelatinized, cassava chips or slices (*ighu)* (20kg) were milled, sieved and also packaged. The flour samples were stored in air tight plastic containers at room temperature until used.

## 2.2 Feed Composition and Screw speed

Cassava flour and African yam bean were blended in the ratios of (0.54:99.46, 20:80, 50:50, 80:20, 99.46:0.54). Also *Ighu* and AYB were blended in the same ratio as that of cassava/AYB (0.54:99.46, 20:80, 50:50, 80:20, 99.46: 0.54). The screw speed of the different extrusion runs were varied from 109.95, 125, 150, 175 and 190.05) rpm.

## 2.3 Moisture Adjustment

The moisture content of cassava flour, *ighu* and AYB were 11%, 12% and 10.02% respectively before adjustment. The moisture content of the blends were adjusted by adding a predetermined amount of water using material balance equation to yield (13.3, 16, 20, 24 and 26.7)% moisture levels of the samples.

## 2.4 Experimental Design and Extrusion Runs

Combination of feed moisture, feed composition and screw speed were determined using a central composite design [7]. Twenty blends of cassava flour and AYB and another 20 blends of *Ighu* flour and AYB were formulated with eight ($2^3$) factorial points, six star points and six center points.

The wetted blends were extruded using single screw extruder (Bradender Duiburg DCE-330, Germany) of a grooved barrel length to diameter ratio (L/D) of 20:1 with variable speed of 0 – 200 rpm and compression ratio of 4: 1 was used for the runs. The die nozzle diameter and length were 2.2 and 40 mm, respectively. The extruder temperatures were fixed at $90^0$C, 120ºC and 110ºC at feed, melt and die zones respectively. The screw speeds were varied from 109.95 to 190.05rpm as described [4]. The operating ranges of the extrusion process were shown in Table 1.

**Table 1. Operating ranges of the extrusion process**

| **Independent Variable** | **Extrusion Conditions** | | | | |
|---|---|---|---|---|---|
| | **-∝** | **-1** | **0** | **+1** | **+∝** |
| Screw Speed (rpm) | 109.95 | 125 | 150 | 175 | 190.05 |
| Moisture Content (%) | 13.27 | 16 | 20 | 24 | 26.73 |
| Feed Composition (%) | 0.54 | 20 | 50 | 80 | 99.46 |

## 2.4 Extrusion Torque (T)

Torque (T) was read directly from the torque indicator on the control panel of the extruder as each sample was collected and reported in Nm. Means of triplicate readings were recorded for each run.

### 2.5 Specific Mechanical Energy (SME)

The specific mechanical energy (SME) was measured as the product of torque and screw speed over the mass flow rate. Torque and screw speed were measured directly as the extrusion runs were going on.

$$SME = \frac{T \times SS}{M} \quad (1)$$

Where M is the mass flow rate

### 2.6 Statistical and Data Analysis

Matlab 7.1 version was used to analyze statistically the data generated and fitted into a quadratic polynomial equation of the type

$$Y = b_o + b_1X_1 + b_2X_2 + b_3X_3 + b_{11}X_1^2 + b_{22}X_2^2 + b_{33}X3^2 + b_{12}X_1X_2 + b_{13}X_1X_3 + b_{23}X_2X_3 \quad (2)$$

The coefficient of determination ($R^2$) were computed. A three dimensional response surface plots were made after removal of the non-significant terms for each response, by holding the variable with the least effect on the response equal to a constant value and changing the other two variables. The critical values were obtained using linear programming.

## 3. RESULTS AND DISCUSSION

### 3.1 Torque

The response surface regression results for torque of the extrudates were shown on Tables 2 and 3. There were significant differences ($P < 0.05$) on the torque of the extruder in the linear, quadratic and interactive effects of screw speed and feed composition for the extruded blends of *Ighu/*AYB, but the moisture content was not significant for both the linear and quadratic effects. The result of the model explained 80.6% of the total variation. The ANOVA results were highly significant ($P < 0.05$). The resulting polynomial equation after removing the non significant terms is

$$Torque_i = 0.216117 + 0.001489SS - 0.002465FC - 0.000002SS^2 + 0.000007FC^2 - 0.000036MC*SS + 0.000019MC*FC - 0.000004SS*FC \quad (3)$$

The response surface plot in Fig. 1 showed that the minimum torque of 0.00075.71kg occurred at critical values of the independent variables and at feed composition of 0.54% and moisture content of 13.36%.

The result showed that the lowest torque occurred at the lowest moisture content and feed composition. Water serves as a lubricant in the extruder. An increase in the extrusion moisture reduced the friction between the extruded material and both screw shaft and cooling die, which reduces the torque and pressure [8,9]. High feed moisture results to decrease in expansion ratio [10].

The estimated response surface regression of torque for the extruded blends of cassava/AYB (Table 3) showed no significant differences in all the independent variables in the linear, quadratic and interactive effects on the torque. The response surface plot in Fig. 2 showed that minimum torque of 0.0156 KJ occurred at critical values of the independent variables of feed composition of 0.702% and moisture content of 26.73%.The variation in the two results (Figs. 1 and 2) may be attributed to the variation in feed composition and the models. *Ighu* flour contained pre-gelatinized cassava starch unlike the cassava flour. The effect of process variables on torque confirms the effect of these variables on product transformation.

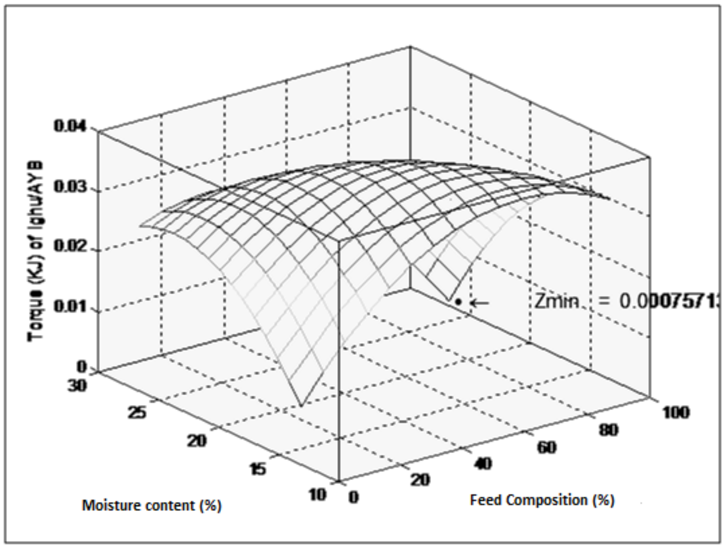


**Fig. 1. Effect of Moisture content and Feed composition on the Torque of extruded *Ighu/AYB* blends**

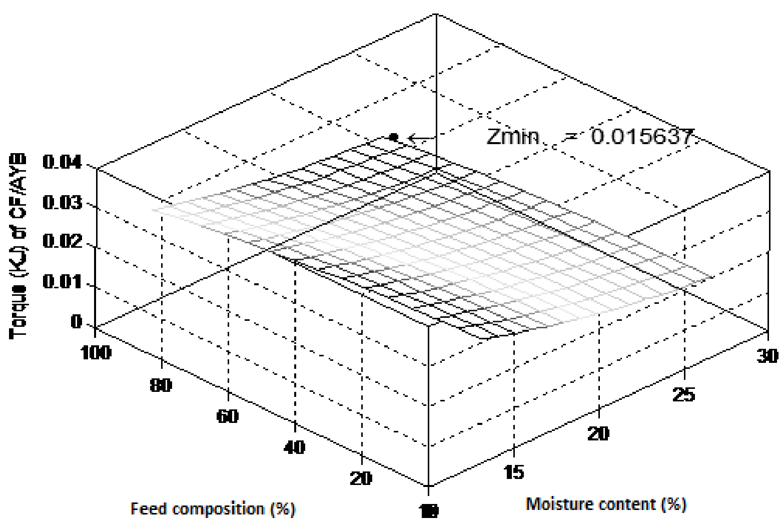


**Fig. 2. Effect of moisture content and feed composition on the torque of extruded Cassava/AYB blends**

The torque indicated the resistance load on the motor. The torque required to turn the extrusion screw was related to its speed, fill and the viscosity of the feed material in the screw channel [5]. A linear relationship had been established between screw speed and torque. Increase in screw speed resulted to a reduction in torque [11,12]. Screw speed has generally a positive effect on extrudate expansion due to the increase in shear and thus overall and radial expansion as well as pore volume [10]. Increase in screw speed has also been noted to increase shear and subsequent internal temperature leading to increase in product flow and reduced residence time and less work for the extruder motor [15]. Torque is sensitive to changes in operating conditions and therefore appeared to be a good control variable.

**Table 2. Response Surface Regression Parameters for Influence of Process Variables on Torque of the Extruded Blends of *Ighu/AYB***

**(a) Regression Coefficients**

| Term | coefficient | SE Coefficient | p |
|---|---|---|---|
| Constant | 0.22 | 0.03 | 0.01 |
| MC | -0.01 | 0.01 | 0.393 |
| SS | 0.01 | 0.01 | 0.01* |
| FC | -0.01 | 0.01 | 0.01* |
| $MC^2$ | -0.01 | 0.01 | 0.91 |
| $SS^2$ | -0.02 | -0.02 | 0.01* |
| $FC^2$ | 0.01 | 0.01 | 0.01* |
| MC*SS | -0.01 | 0.01 | 0.01* |
| MC*FC | 0.01 | 0.01 | 0.01* |
| SS*FC | -0.01 | 0.01 | 0.01* |
| S = 0.004167 | $R^2$ = 80.6% | | $R^2$(adj)= 78.7% |

**(b) Analysis of Variance (ANOVA)**

| Source | DF | Seq SS | Adj SS | Adj MS | F | P |
|---|---|---|---|---|---|---|
| Regression | 9 | 0.01 | 0.01 | 0.01 | 41.65 | 0.01* |
| Linear | *3* | 0.01 | 0.01 | 0.01 | 56.66 | 0.01* |
| Square | 3 | 0.01 | 0.01 | 0.01 | 27.99 | 0.01* |
| Interaction | 3 | 0.01 | 0.01 | 0.01 | 24.37 | 0.01* |
| Residual Error | 90 | 0.01 | 0.01 | 0.01 | | |
| Pure Error | 85 | 0.01 | 0.01 | 0.01 | | |
| Total | 99 | 0.01 | | | | |

**significant at p =0.05*

The estimated response surface regression of torque for the extruded blends of cassava/AYB (Table 2) showed no significant differences in all the independent variables in the linear, quadratic and interactive effects on the torque. The results showed that none of the processing variables had significant influence on the extruder torque of cassava/ AYB blend. The coefficient of determination ($R^2$ =26.5%) and the lack of fit been significant (P< 0.05) indicated that the model did not fit. The response surface plot in Fig. 2 showed that minimum torque of 0.0156 KJ occurred at critical values of the independent variables of feed composition of cassava/AYB of 0.702% and moisture content of 26.73%. The variation in the two results of ighu/AYB and cassava/AYB blend may be attributed to the variation in their feed composition and the models. Ighu is pre-gelatinized while cassava flour was not. Their starch component must have reacted differently in the extruder. The results were in agreement that increase in feed composition (starch and protein) lead to increase in torque value [15]. The effect of process variables on torque confirms the effect of these variables on product transformation.

**Table 3. Response Surface Regression Parameters for Influence of Process Variables on Torque of the Extruded Blends of Cassava/AYB**

**(a) Regression Coefficients**

| Term | Coef | SE Coef | P |
|---|---|---|---|
| Constant | 0.09 | 0.05 | 0.057 |
| MC | -0.01 | 0.02 | 0.474 |
| SS | -0.01 | 0.01 | 0.277 |
| FC | -0.01 | 0.01 | 0.292 |
| $MC^2$ | 0.01 | 0.01 | 0.056 |
| $SS^2$ | 0.01 | 0.01 | 0.611 |
| $FC^2$ | 0.01 | 0.01 | 0.068 |
| MC*SS | -0.02 | 0.01 | 0.847 |
| MC*FC | 0.01 | 0.01 | 0.090 |
| SS*FC | 0.01 | 0.01 | 0.404 |
| S = 0.01 | $R^2$ =26.5% | | $R^2$(adj) = 19.2% |

**(b) Analysis of Variance (ANOVA)**

| Source | DF | Seq SS | Adj SS | Adj Ms | F | P |
|---|---|---|---|---|---|---|
| Regression | 9 | 0.01 | 0.01 | 0.01 | 3.61 | 0.01 |
| Linear | 3 | 0.01 | 0.01 | 0.01 | 0.71 | 0.55 |
| Square | 3 | 0.01 | 0.01 | 0.01 | 2.20 | 0.09 |
| Interaction | 3 | 0.01 | 0.01 | 0.01 | 1.26 | 0.29 |
| Residual Error | 90 | 0.01 | 0.01 | 0.01 | | |
| Lack-of-Fit | 5 | 0.01 | 0.01 | 0.01 | 190.33 | 0.01 |
| Pure Error | 85 | 0.01 | 0.01 | 0.01 | | |
| Total | 99 | 0.01 | | | | |

**significant at p=0.05*

### 3.2 Specific Mechanical Energy (SME)

The result of the regression analysis for extruded blends of *Ighu/AYB* (Table 4) showed that there were significant differences ($p < 0.05$) in the linear, quadratic and interactive effects of SME on the independent variables except for the linear effect of moisture content and the interactive effect of the SS. The model explained 65.4% of the total variation. The polynomial equation after removing the non-significant terms becomes

$$SME_i = 114.912 + 2.879SS - 1.512FC - 0.131MC^2 + 0.003FC^2 - 0.068MC*SS - 0.013SS*FC \quad (4)$$

The response surface plots in Fig. 3 showed that the maximum SME of 99.0227 KJ/KG occurred at the combination of the critical values of screw speed and feed composition of 192.05rpm and 0.54% respectively.

The response surface regression analysis for extruded blends of cassava/AYB in Table 5 showed significance ($p < 0.05$) in the linear and interactive effects of moisture content. The ANOVA result also showed significance in the linear and interactive effects. The model explained 52.3% of the total variation. The polynomial equation after removal of non linear equation becomes

$$SMEc = 234.287-13.104MC-0.058MC*SS+0.061MC*FC-0.008SS*FC \quad (5)$$

The response surface plot in Fig. 4 showed that maximum SMEc value of 95.5448KJ/KG occurred at the combination of critical variables of screw speed of 192.05rpm and moisture content of 13.26%. The difference in the results. The result showed that reduction in moisture content of the feed materials resulted to an increase in the SME of the extruder. The results were in agreement with the report of [13] who increased the extruder SME by reducing the moisture content of the feed and adding reverse screw elements, which resulted to increased expansion and breaking strength in extruded corn, potato or rice snacks.

The SME input is a good quantitative description in extrusion processes, since it allows the direct comparison of different combination of extrusion conditions such as screw speed, feed rate, and torque. The amount of mechanical energy delivered to the extruded material determines the extent of macromolecular transformation and interaction that took place, that is starch conversion and consequently rheological properties of the melt [14]. SME is relevant in that the more the energy applied, the greater the degradation of starch, while torque is directly correlated with power usage [12].

**Table 4. Response Surface Regression Parameters for Influence of Process Variables on Specific Mechanical Energy of the Extruded Blends of *Ighu/AYB***

**(a) Regression Coefficients**

| Term | Coef | SE Coef | P |
|---|---|---|---|
| Constant | 114.91 | 63.91 | 0.08 |
| MC | 0.24 | 3.26 | 0.94 |
| SS | 2.88 | 0.37 | 0.01* |
| FC | -1.51 | 0.57 | 0.01* |
| $MC^2$ | -0.13 | 0.06 | 0.04* |
| $SS^2$ | 0.01 | 0.01 | 0.07 |
| $FC^2$ | 0.01 | 0.01 | 0.04* |
| MC*SS | 0.01 | 0.01 | 0.01 |
| MC*FC | -0.07 | 0.01 | 0.01 |
| SS*FC | 0.05 | 0.01 | 0.01 |
| S =8.472 | $R^2$ = 65.4% | | $R^2$(adj) = 61.9% |

**(b) Analysis of Variance (ANOVA)**

| Source | DF | Seq SS | Adj SS | Adj MS | F | P |
|---|---|---|---|---|---|---|
| Regression | 9 | 12192.0 | 12192.0 | 1354.67 | 18.88 | 0.01* |
| Linear | 3 | 3695.6 | 5399.4 | 1799.82 | 25.08 | 0.01* |
| Square | 3 | 938.6 | 938.6 | 312.85 | 4.36 | 0.01* |
| Interaction | 3 | 7557.9 | 7557.9 | 2519.30 | 35.10 | 0.01* |
| Residual Error | 90 | 6459.0 | 6459.0 | 71.77 | | |
| Pure Error | 85 | 3408.6 | 3408.6 | 40.10 | | |
| Total | 99 | 18651.0 | | | | |

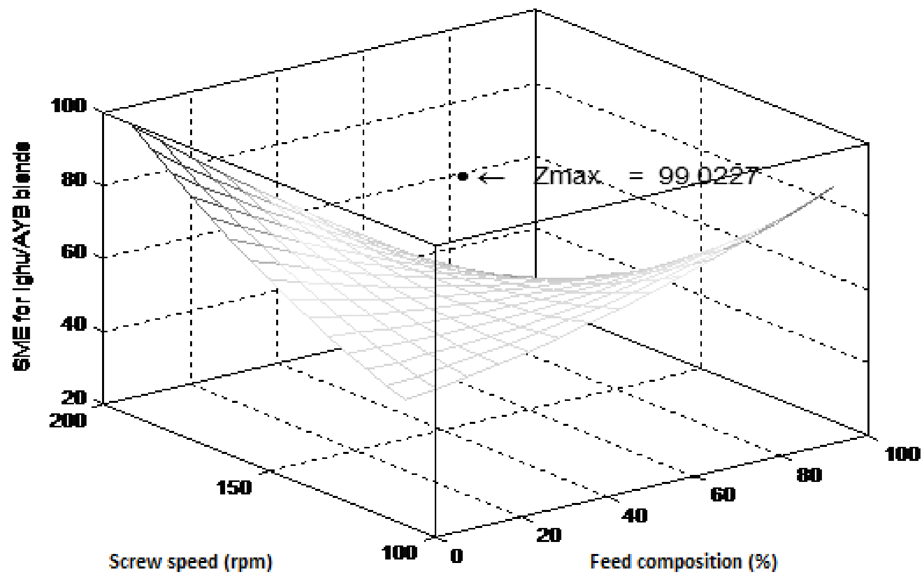


**Fig. 3. Effect of Feed composition and Screw speed on the SME of extruded *Ighu/AYB* blends**

**Table 5. Response Surface Regression Parameters for Influence of Process Variables on Specific Mechanical Energy of the Extruded Blends of Cassava/AYB**

**(a) Regression Coefficients**

| Term | Coef | SE Coef | P |
|---|---|---|---|
| Constant | 234.29 | 61.22 | 0.01* |
| MC | -13.11 | 3.12 | 0.01* |
| SS | -0.32 | 0.35 | 0.36 |
| FC | -0.61 | 0.55 | 0.27 |
| $MC^2$ | 0.02 | 0.06 | 0.74 |
| $SS^2$ | 0.01 | 0.01 | 0.19 |
| $FC^2$ | -0.01 | 0.01 | 0.61 |
| MC*SS | 0.06 | 0.01 | 0.01* |
| MC*FC | 0.06 | 0.01 | 0.01* |
| SS*FC | -0.01 | 0.01 | 0.01* |
| S = 8.12 | $R^2$ = 52.3% | | $R^2$(adj) = 47.5% |

**(b) Analysis of Variance (ANOVA)**

| Source | DF | Seq SS | Adj SS | Adj MS | F | P |
|---|---|---|---|---|---|---|
| Regression | 9 | 6492.0 | 6492.0 | 721.33 | 10.95 | 0.01* |
| Linear | 3 | 1693.7 | 1185.4 | 395.12 | 6.00 | 0.01* |
| Square | 3 | 144.7 | 144.7 | 48.24 | 0.73 | 0.54 |
| Interaction | 3 | 4653.5 | 4653.5 | 1551.16 | 23.55 | 0.01* |
| Residual Error | 90 | 5927.0 | 5927.0 | 65.86 | | |
| Pure Error | 85 | 203.2 | 203.2 | 2.39 | | |
| Total | 99 | 12419.0 | | | | |

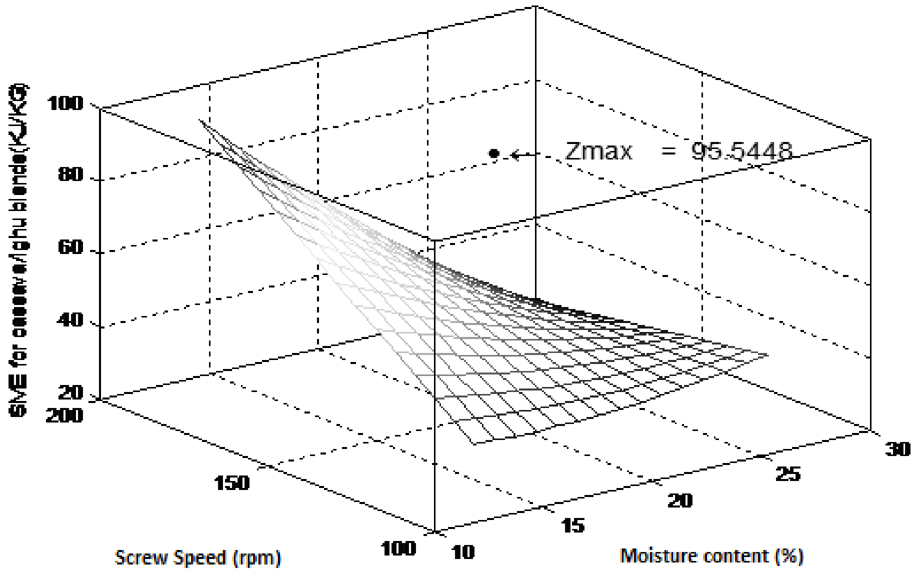


**Fig. 4. Effect of Moisture content and Screw speed on the SME of extruded Cassava/AYB blends.**

## 4. CONCLUSION

The specific mechanical energy and torque of the single screw extruder were influenced by the independent variables (screw speed, feed composition and feed moisture content). The torque was significantly different (P<0.05) in the linear, quadratic and interactive effects of screw speed and feed composition of extruded blends of *Ighu*/AYB but that of cassava/AYB blend were not significant (p> 0.05).The pre-gelatinization of the ighu flour had a milder effect on the energy efficiency of the single screw extruder than the cassava flour.

## COMPETING INTERESTS

Authors have declared that no competing interests exist.

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