

Optimization of the Residence Time and Throughput in a Single Screw Extrusion of Cassava/African yam bean Mixtures.

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ABSTRACT

The influence of extrusion cooking variables on the residence time and throughput of a single screw extruder were investigated using blends of African yam bean (AYB) and cassava flour. The main purpose was to optimize the throughput and residence time of AYB/cassava extrusion using three operating variables (screw speed (SS), feed moisture content (MC) and feed composition (FC)). African yam bean and cassava tubers were processed into flours. A central composite design (CCD) was used to determine the feed moisture content, feed composition and the screw speed used in the operation. Twenty extrusion runs were conducted with eight (2^3) factorial, six star points and six central points. The throughput (TP) and residence time (RT) were determined using standard procedures. Data obtained were subjected to response surface analysis (RSA) and ANOVA. The results of the response surface regression of TP showed that SS was highly significant in the linear, quadratic and interactive effects. The critical throughput values were 0.098Kg/min for combination of screw speed and moisture content and 0.084Kg/min for combination of feed composition and moisture content variables. The residence time increased as the moisture content and screw speed decreased. The critical residence time values of 59.94s and 28.63s were obtained. The results confirmed that residence time was inversely proportional to screw speed and moisture content.

Keywords: Response surface analysis, residence time, throughput, screw speed, feed composition, moisture content.

1. INTRODUCTION

Extrusion is a powerful food processing operation, which utilizes high temperature and high shear force to produce a product with unique physical and chemical characteristics (Pansawat et al., 2008). The operating conditions and the rheological properties of the food are the two major factors that influence the nature of the extruded products (Fellows, 2000). The choice of the extruder depends on raw material and the desired end product (Riaz, 2000).

Response surface analysis provide an effective means for the study and the optimization of operating conditions in extrusion technology. 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. CCD and RSM have been used also by several researchers in optimizing food processing operations (Nwabueze,2004; Chang and El-Dash 2003; Nwabueze and Iwe, 2007; Filli et al.,2012).

To achieve optimum results, it is very necessary to determine proper combinations of screw speed, moisture content and feed composition of the operation and to investigate the impact of these variables on the extruder. The use of proper feed formulation and moisture content in addition to screw speed of extruder provide pre-cooked or quick to cook blends of AYB/cassava products.

2. MATERIALS AND METHODS

2.1 Sample Preparation

Creamed coloured variety of African yam bean (*Sphenostylis stenocarpa*) seeds and Cassava (*Manihot exculenta*, c) tubers were used for the study. All the sample materials were processed into flour. The flour samples were stored in air tight plastic containers at room temperature ($30 \pm 1^{\circ}\text{C}$) until used.

2.2 Experimental Design and Extrusion Runs

Combination of feed moisture, feed composition and screw speed were determined using a central composite design (Chang and El-Dash 2003). Twenty blends of cassava flour and AYB were formulated with eight (2^3) factorial points, six star points and six center points as shown in (Table 1).

Table 1: Operating ranges of the Extrusion Process

Independent Variable	Extrusion Conditions				
	$-\infty$	-1	0	+1	$+\infty$
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

The moisture levels of the flour were determined before the extrusion process. 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 levels of the samples. The flour samples were then mixed and transferred into polythene bags and allowed to equilibrate for 12 hours at room temperature ($28 \pm 1^{\circ}\text{C}$).

The wetted blends were extruded using single screw extruder (Bradender Duisburg DCE-330, Germany) under different operating conditions (Table 2). The extruder temperatures were fixed at 90°C , 120°C and 110°C at feed, melt and die zones respectively. The screw speeds were varied from 109.95 to 190.05rpm.

Table 2: Experimental design for Cassava/AYB flour blends: Coded Variables and real processing value.

Exp. No.	Coded Variables			Process Variables		
	x ₁	x ₂	x ₃	X ₁	X ₂	X ₃
1	-1	-1	-1	125	16	20:80
2	-1	-1	1	125	16	80:20
3	-1	1	-1	125	24	20:80
4	-1	1	1	125	24	80:20
5	1	-1	-1	175	16	20:80
6	1	-1	1	175	16	80:20
7	1	1	-1	175	24	20:80
8	1	1	1	175	24	80:20
9	-∞	0	0	109.95	20	50:50
10	∞	0	0	190.05	20	50:50
11	0	-∞	0	150	13.27	50:50
12	0	∞	0	150	26.73	50:50
13	0	0	-∞	150	20	0.54:99.46
14	0	0	∞	150	20	99.46:0.54
15	0	0	0	150	20	50:50
16	0	0	0	150	20	50:50
17	0	0	0	150	20	50:50
18	0	0	0	150	20	50:50
19	0	0	0	150	20	50:50
20	0	0	0	150	20	50:50

x₁ and X₁= Screw Speed (rpm), x₂ and X₂ = Moisture content (%)

x₃ and X₃=Feed composition(%)

After extrusion cooking, the extrudates (plate 1) were oven dried at 60 ± 1 °C for 10hrs to obtain dried extrudates.



PLATE 1: PHOTOGRAPH OF EXTRUDATES BEFORE PACKAGING

2.3 Residence Time (RT)

The extrusion process was allowed to run until steady state condition was attained. The residence time was determined using red food colour as a tracer. 0.5g of red food colour was introduced at the feeding port and emerging samples collected until the red die was no longer visible. The minimum residence time (RT) the feed particles spent in the extruder from introduction of the red food colour indicator at the extruder feed port until it appeared at the die was noted. The extrudate collection time (T_i) being the total time from the emergency of first colour (T_o) at the die to disappearance of colour was also noted. ($RT = T_i - T_o$).

2.4 Throughput (TP)

The throughput or mass flow rate was calculated by measuring the mass of the extrudate obtained within one minute.

2.5 Statistical and Data Analysis

Data generated from the study were statistically analysed using Matlab 7.1 version and fitted into a quadratic polynomial equation of the type

$$Y = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_{11}X_1^2 + b_{22}X_2^2 + b_{33}X_3^2 + b_{12}X_1X_2 + b_{13}X_1X_3 + b_{23}X_2X_3 \quad \dots\dots\dots(1)$$

Where Y = the response, X_1 = screw speed, X_2 =moisture content, X_3 = feed composition, b_0 =intercepts, b_1, b_2, b_3 are linear, b_{11}, b_{22}, b_{33} are quadratic and b_{12}, b_{13} and b_{23} are interaction regression coefficient terms.

The coefficients 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 Throughput (TP)

The results of the estimated regression coefficient for throughputs were shown in (Tables 3). There were significant differences ($P < 0.05$) in the linear, quadratic and interactive effects of feed composition on TP of the blends. Increase in the level of African yam bean in the feed material resulted to increase in the rate of flow in the extruder, the result may be attributed to the supposed increase in the amount of protein and fat in the African yam bean (feed material). The result also showed that the SS was highly significant in the linear, quadratic and interactive effects. As expected, screw speed had significant effect on TP since it is the mass flow rate, it increased as the rate of rotation of the screw increased. The model contributed 75.6% of the total variation on TP. The lack of fit was highly significant and there was also significance ($P < 0.05$) in the ANOVA results confirming the regression results. The polynomial equation after removing the non significant terms becomes:

$$\begin{aligned} \text{TPc} = & -0.090146 + 0.000717\text{SS} + 0.001807\text{FC} + 0.0001\text{MC}^2 - 3 \times 10^{-6}\text{SS}^2 - \\ & 3.9 \times 10^{-5}\text{MC} \times \text{SS} - 0.000043\text{MC} \times \text{FC} - 9 \times 10^{-6}\text{SS} \times \text{FC} \text{ ----- (2)} \end{aligned}$$

The significant difference effect of SS on TP was in agreement with the report of Nwabueze (2004) on extruded blends of African bread fruit, corn and soybean. Throughput plays important role in scale up and the determination of optimal process conditions for mixing, dispersing and polymerization applications.

Table 3: Response Surface Regression Parameters for Influence of Process Variables on Throughput of the Extruded Blends of Cassava/AYB

(a) Regression Coefficients

Term	Coef	SE Coef	T	P
Constant	-0.090146	0.041299	-2.183	0.032
MC	0.001452	0.002104	0.690	0.492
SS	0.000717	0.000238	3.011	0.003
FC	0.001807	0.000368	4.906	0.000
MC ²	0.000100	0.000040	2.489	0.015
SS ²	-0.000003	0.000001	-4.053	0.000
FC ²	-0.000002	0.000001	-1.977	0.051
MC*SS	0.000039	0.000007	5.401	0.000
MC*FC	-0.000043	0.000009	-4.968	0.000
SS*FC	-0.000009	0.000001	-8.000	0.000
S = 0.005475 r ² = 75.6% r ² (adj) = 73.2%				

(b) Analysis of Variance (ANOVA)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	9	0.008377	0.008377	0.000931	31.06	0.000
Linear	3	0.004000	0.000940	0.000313	10.45	0.000
Square	3	0.000846	0.000846	0.000282	9.41	0.000
Interaction	3	0.003532	0.003532	0.001177	39.28	0.000
Residual Error	90	0.002697	0.002697	0.000030		
Lack-of-Fit	5	0.000945	0.000945	0.000189	9.16	0.000
Pure Error	85	0.001753	0.001753	0.000021		
Total	99	0.011075				

The response surface plot in (Fig. 1 and Fig. 2) revealed maximum throughput of 0.0982Kg/min and 0.0846Kg/min for screw speed and moisture content and for moisture content and feed composition for extruded blends of cassava /AYB respectively.

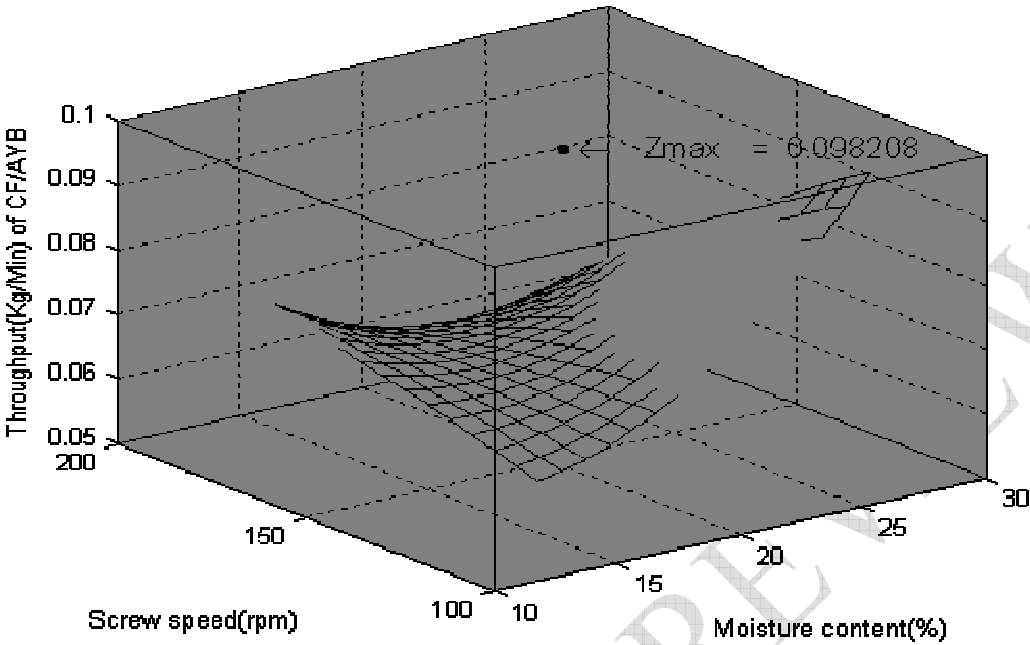


Fig 1: Effect of Screw speed and Moisture content on the Throughput of extruded Cassava/AYB blends.

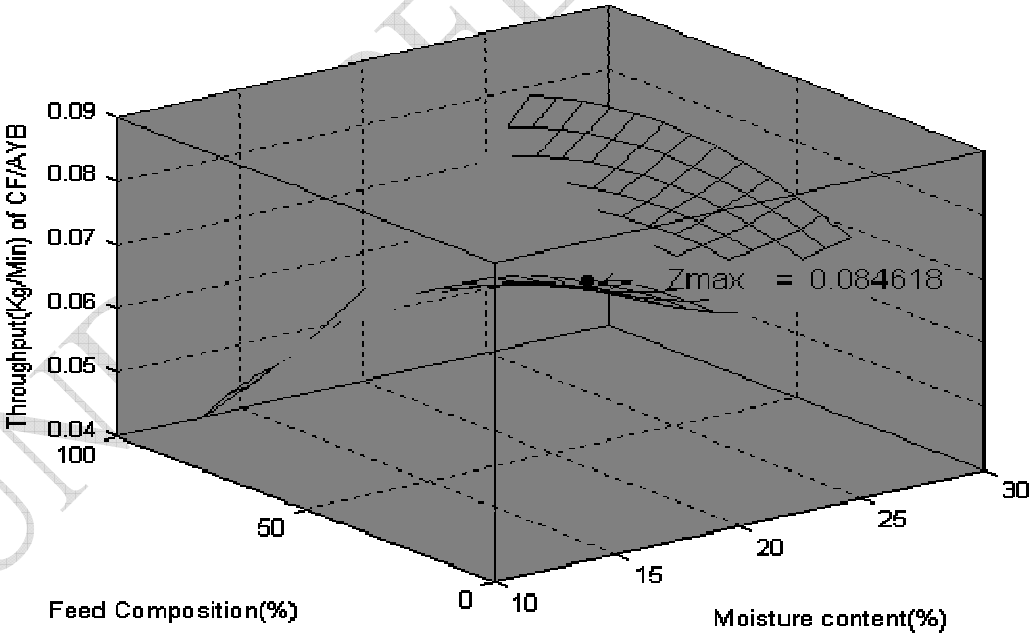


Fig 2: Effect of Moisture content and Feed composition on the Throughput of extruded Cassava/AYB blends.

3.2 Residence Time (RT)

The response surface regression result of the extruded blends of cassava/AYB (Table 4) showed significant differences ($p < 0.05$) in the linear, quadratic and interactive effects of the screw speed on the residence time. The analysis of variance (ANOVA) result showed high significance $p < 0.05$ in all the effects. The polynomial equation after removing the non significant terms becomes

$$RT_c = 405.71 - 10.829MC - 0.367SS - 3.384FC + 0.124MC^2 + 0.007FC^2 - 0.033MC*SS + 0.048MC*FC + 0.006SS*FC \quad \text{-----} \quad (3)$$

Table 4: Response Surface Regression Parameters for Influence of Process Variables on Residence Time of Cassava/AYB

(a) Regression Coefficients

Term	Coef	SE Coef	T	P
Constant	405.713	42.2257	9.608	0.000
MC	-10.829	1.9101	-5.669	0.000
SS	-0.367	0.1726	-2.129	0.035
FC	-3.384	0.3554	-9.522	0.000
MC ²	0.124	0.0418	2.956	0.004
SS ²	0.001	0.0008	0.699	0.486
FC ²	0.007	0.0011	6.517	0.000
MC*SS	-0.033	0.0049	-6.777	0.000
MC*FC	0.048	0.0059	8.048	0.000
SS*FC	0.006	0.0008	7.201	0.000
S = 5.008	r ² = 71.3%		r ² (adj) = 69.3%	

(b) Analysis of Variance (ANOVA)

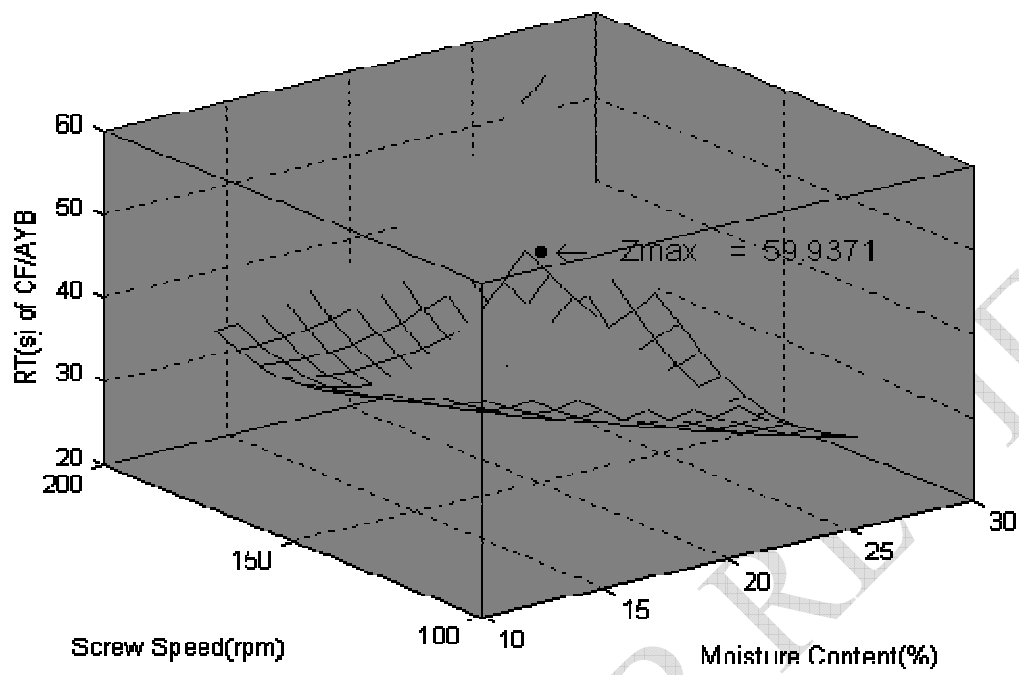
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	9	7799.3	7799.35	866.59	34.55	0.000
Linear	3	2230.2	2311.57	770.52	30.72	0.000
Square	3	1492.1	1492.11	497.37	19.83	0.000
Interaction	3	4077.0	4077.00	1359.00	54.19	0.000
Residual Error	125	3135.1	3135.05	25.08		
Lack-of-Fit	5	3135.1	3135.05	627.01	*	*
Pure Error	120	0.0	0.00	0.00		
Total	134	10934.4				

The response surface plot in (Fig 3) showed maximum residence time of 59.93s at the critical moisture content value of 13.26% and screw speed of 109.45rpm which were the minimum values used for moisture content and screw speed while the response surface plot in (Fig.4) revealed minimum residence time of 28.63s at the critical moisture content value of 26.73% and screw speed of 125.47rpm.

The result revealed that RT decreased as the moisture content and screw speed increased. The results were in agreement with the report of Nwabueze and Iwe (2007) who observed that extrudates spent longer time in the extruder as feed moisture or screw speed decreased from 27% to 15% or 180rpm to 100rpm respectively, thereby increasing the residence time distribution characteristics. Also Davidson *et al.* (1983) reported a reduction in average RT in a single screw extruder at increased screw speed. Increase in screw speed enhanced breakthrough time, while a decrease in screw speed enhanced mean RT (Zhu, 1998; Iwe *et al*, 2001). Increase in moisture content of the feed material led to lubrication of the screw and resultant easier flow of the particles. The ease of discharge of extrudate from the die is a function of the friction imposed.

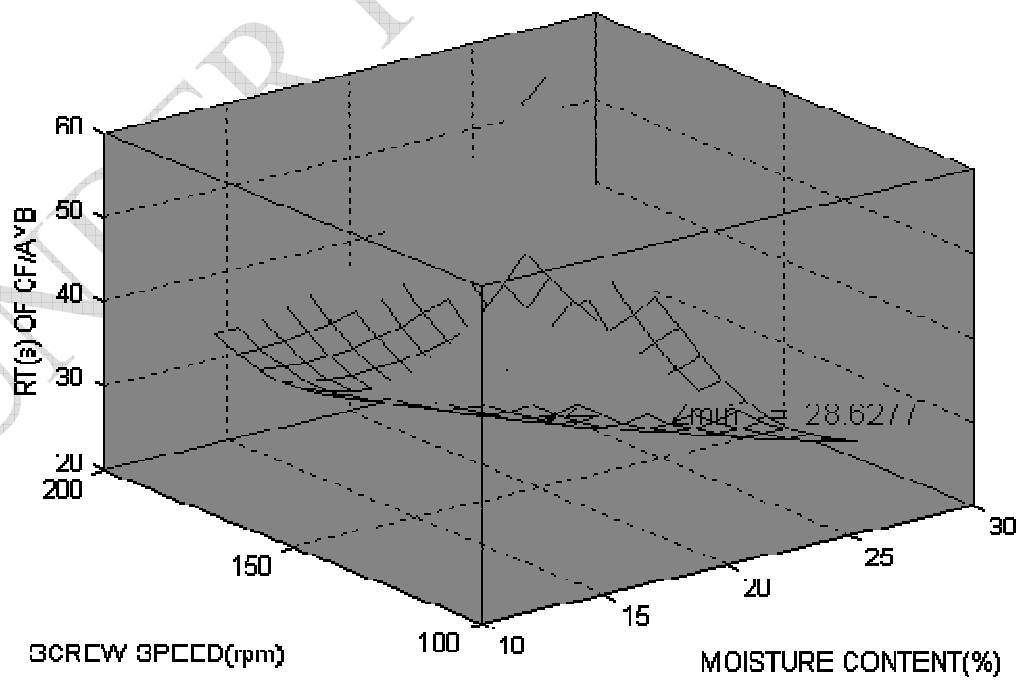
The result revealed that extrusion of AYB was easier and faster than extrusion of cassava products, which may be attributed to the percentage of oil and protein in the AYB and its nature. The feed composition especially the feed oil and protein content and the feed particle size and texture affected the RT. Increase in AYB content resulted to increase in protein content of the feed and subsequent increase in protein-protein interaction at higher levels of protein concentration Onwulata *et al*,(1998), while the higher the starch content, the more viscous the nature of the mixture during extrusion and the more the difficulty of the exit of the extrudate from the die (Van Zuilichem *et al*, 1973; Van Zuilichem 1992; Iwe *et al.*, 2001).

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Fig 3: Effect of Moisture content and Screw speed on the Residence Time of extruded Cassava/AYB blends.



232

Fig 4: Effect of Screw speed and Moisture content on the Residence Time of extruded Cassava/AYB.

4.0 CONCLUSIONS

The study of the residence time is a useful tool in determining the essence of cook of the extrudate and the quality of the product in terms of nutritional, organoleptic and consumer acceptance. The throughput and residence time of the feed materials inside the extruder were all affected by the independent variables (screw speed, feed composition and feed moisture). The model equations and the correlation coefficients established can be used to predict the optimal residence time distribution and throughput of casava/AYB extrudates, which the response plots. The RSA was found to be an easier option to investigate the residence time and throughput of the extrudate, also the influence of the three variables on the residence time and throughput response were achieved which would have been cumbersome using the conventional methods of analysis.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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