

Influence of Extrusion Variables on the Residence Time and Throughput of a Single Screw Extruder.

G.C. Omeire^{1*}, M. O. Iwe² and J. N.Nwosu¹

Corresponding Phone number: 08065179082 e-mail: comeire@yahoo.com

¹Department of Food Science and Technology, Federal University of Technology, Owerri
P.M.B.1526 Owerri, Imo State Nigeria

²Department of Food Science and Technology, Michael Okpara University of Agriculture,
Umudike

P.M.B.7267 Umuahia, Abia State Nigeria

ABSTRACT **Aims:** 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)).

Study design: 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.

Place and Duration of Study: The cassava tubers were obtained from National Research Institute, Umudike Abia State, the AYB from a local market in Abia State Nigeria and the extrusion work was done at Federal Polytechnic Mubi Adamawa State Nigeria.

28 **Methodology:** Twenty extrusion runs were conducted with eight (2^3) factorial, six star points
29 and six central points. The throughput (TP) and residence time (RT) were determined using
30 standard procedures. Data obtained were subjected to response surface analysis (RSA) and
31 ANOVA.

32 **Results:** The results of the response surface regression of TP showed that SS was highly
33 significant in the linear, quadratic and interactive effects. The critical throughput values were
34 0.098Kg/min for combination of screw speed and moisture content and 0.084Kg/min for
35 combination of feed composition and moisture content variables. The residence time
36 increased as the moisture content and screw speed decreased. The critical residence time
37 values of 59.94s and 28.63s were obtained.

38 **Conclusion:** The results confirmed that residence time was inversely proportional to screw
39 speed and moisture content. The data obtained from the study could be used for control of
40 product characteristics and possible projection for the commercial production of extruded
41 blends of African yam bean and cassava flour using a single screw extruder.

42
43 *Keywords:* Response surface analysis, residence time, throughput, screw speed, feed
44 composition, moisture content.
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47

48 1. INTRODUCTION

49 Extrusion is a powerful food processing operation, which utilizes high temperature and
50 high shear force to produce a product with unique physical and chemical
51 characteristics[1]. The operating conditions and the rheological properties of the food are
52 the two major factors that influence the nature of the extruded products [2]. In the
53 extruders, the components are mixed, sheared and subjected to elevated temperatures
54 and pressures. So that the dough shows a plastic consistency that favours the
55 expansion of product at the exit of the die. In fact, the sudden drop in pressure at the exit
56 of extruder causes the release of gases entrapped in the product, determining the
57 swelling of extrudates [3]. Many factors affect the expansion of the extrudates: type of
58 plant, screw configuration, moisture content of the dough, residence time, operating
59 pressure, temperature profile of the barrel, screw speed and feed capacity [4]. Also the
60 chemical type of material or ingredient used to produce extrudates could have a
61 considerable effect on expansion degree. The presence of lipids for example leads to a
62 compact structure and involves also technological drawbacks: migration of fatty fraction

outside of dough (due to operating temperature and pressure) and, subsequently, percolation oil at the die [5]. Oil loss is not advisable to preserve both the extrudates (quickly oxidation of oil on the extrudate surface) and the hygienic condition of the plant. The oil loss that occurs during extrusion processing of flours with high content of lipids, can be reduced by using an emulsifier [6;7]. However, the addition of this ingredient could influence the structure of the extrudates that could be improved by addition of commercial enzymes [8].

African yam bean (AYB) is one of the lesser known legumes produced in Nigeria. The protein content of AYB ranges from 19.6 – 29% [9]. The lysine and methionine levels were reported to be equal or higher than those of soybean [10]. The amino acid profile obtained for AYB were mostly higher than those obtained for cassava flour. Blending AYB with cassava flour resulted to increase in the amino acid content of the blends, which showed that blending of AYB and cassava products before extrusion marginally improved the nutritional value of the extrudates[11].

The choice of the extruder depends on raw material and the desired end product [12]. Twin-screw extruder is more suitable to extrude fat meals, than the single one because it determines a smaller loss of fat during the process of extrusion and a greater expansion of the products[13]. The fat content of AYB was found to be 2.2% while that of cassava flour was 0.53% which signifies low fat content of the extruded products. Therefore the choice of a single screw extruder.

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. MATERIAL 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 Moisture Adjustment

The initial moisture content of cassava flour was 11% while that of AYB was 10.02% before moisture adjustment. 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. Cassava flour (CF) and AYB flour were mixed at various weight ratios and the total moisture contents of the blends adjusted to the desired values with a mixer. Weights of the components mixed were calculated using the following formula:

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$$C_{CF} = \frac{[r_{CF} \times M \times (100 - w)]}{100 \times (100 - w_{CF})} \quad (1)$$

109

$$C_{AYB} = \frac{[r_{AYB} \times M \times (100 - w)]}{[100 \times (100 - w_{AYB})]} \quad (2)$$

113

$$W_x = M - C_{CF} - C_{AYB} \quad (3)$$

C_{CF} and C_{AYB} are the mass of cassava flour and AYB flours respectively, r_{CF} and r_{AYB} are percentages of cassava flour and AYB flours in the blends respectively.

Percentage dry weight basis (d.w.b); ($r_{CF} + r_{AYB} = 100\%$); M is the total mass of the blend; w , the moisture content of the final blend. Percentage wet weight basis (w.w.b); W_x is the weight of water added; w_{CF} and w_{AYB} are the moisture content of cassava flour and AYB respectively.

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2.3 Experimental Design and Extrusion Runs

Combination of feed moisture, feed composition and screw speed were determined using a central composite design [14]. 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

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Moisture content(%) feed composition(%) CF:AYB

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

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The wetted blends were extruded using single screw extruder (Bradender Duisburg 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 was equipped with heating and cooling mechanisms. The extruder barrel 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. The length of the extruder was 38 cm. The extruder was fed manually through a screw operated conical hopper which ensures the flights of the screw filled and avoiding accumulation of the material in the hopper. The extrusion process was allowed to run for stabilization over a period of 30 minutes at screw speed of 100 rpm before the runs commenced for each set of process variable conditions. The experimental design for the extrusion runs were shown in Table 2.

After extrusion cooking, the extrudates were oven dried at $60 \pm 1^\circ\text{C}$ for 10hrs to obtain dried extrudates. The moisture content of the extrudates after drying ranged from 4.68 % and 6.67 %.

2.4 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.

$$(RT = T_i - T_o) \text{ ----- (4).}$$

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	$-\infty$	0	0	109.95	20	50:50
10	∞	0	0	190.05	20	50:50
11	0	$-\infty$	0	150	13.27	50:50
12	0	∞	0	150	26.73	50:50
13	0	0	$-\infty$	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

160 x1 and X1= screw speed (rpm), x2 and X2 = moisture content (%)

161 x3 and X3=feed composition which is ratio of cassava/AYB (%)

162 2.5 Throughput (TP)

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

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166 2.6 Statistical and Data Analysis

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

169 $Y = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_{11}X_1^2 + b_{22}X_2^2 + b_{33}X_3^2 + b_{12}X_1X_2 + b_{13}X_1X_3 + b_{23}X_2X_3$ (5)
170 Where Y = the response, X_1 = screw speed, X_2 =moisture content, X_3 = feed composition,
171 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
172 regression coefficient terms.

$$173 \quad Y = \beta_0 + \sum_{i=1}^k \beta_i X_i + \sum_{i=1}^k \beta_{ii} X_i^2 + \sum_{i=1}^k \sum_{j=1}^k \beta_{ij} X_i X_j + \varepsilon \quad \text{-----}(6)$$

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

178

179

180 **3. RESULTS AND DISCUSSION**

181 **3.1 Throughput (TP)**

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

$$193 \quad \text{TPc} = -0.090146 + 0.000717\text{SS} + 0.001807\text{FC} + 0.0001\text{MC}^2 - 3 \times 10^{-6}\text{SS}^2 - \\ 194 \quad 3.9 \times 10^{-5}\text{MC} \times \text{SS} - 0.000043\text{MC} \times \text{FC} - 9 \times 10^{-6}\text{SS} \times \text{FC} \quad \text{-----} \quad (7)$$

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196 The significant difference effect of SS on TP was in agreement with the report of Nwabueze
197 (2004) on extruded blends of African bread fruit, corn and soybean. Throughput plays
198 important role in scale up and the determination of optimal process conditions for mixing,
199 dispersing and polymerization applications.

200 The response surface plot in (Fig. 1 and Fig. 2) revealed maximum throughput of
201 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. The results showed that the maximum throughput of 0.0982Kg/min was obtained when the screw speed was set at 109.95 rpm and the moisture content of the blend was 26.73%. Similarly, the maximum throughput of 0.0846Kg/min was also obtained when the moisture content was 13.26% and feed composition was 0.54% cassava flour. The information could be used in designing of a process reactor or for scale up production of commercial extruded products from blends of cassava/AYB.

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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	P
Constant	-0.09	0.04	0.03
MC	0.01	0.01	0.49
SS	0.01	0.01	0.01*
FC	0.01	0.01	0.01*
MC ²	0.01	0.01	0.02*
SS ²	-0.01	0.01	0.01*
FC ²	-0.01	0.01	0.05
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 = 0.01	R ² = 75.6%		R ² (adj) = 73.2%

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(b) Analysis of Variance (ANOVA)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	9	0.01	0.01	0.01	31.06	0.01

Linear	3	0.01	0.01	0.01	10.45	0.01
Square	3	0.01	0.01	0.01	9.41	0.01
Interaction	3	0.01	0.01	0.01	39.28	0.01
Residual Error	90	0.01	0.01	0.01		
Lack-of-Fit	5	0.01	0.01	0.01	9.16	0.01
Pure Error	85	0.01	0.01	0.01		
Total	99	0.01				

significant at $P=0.05$

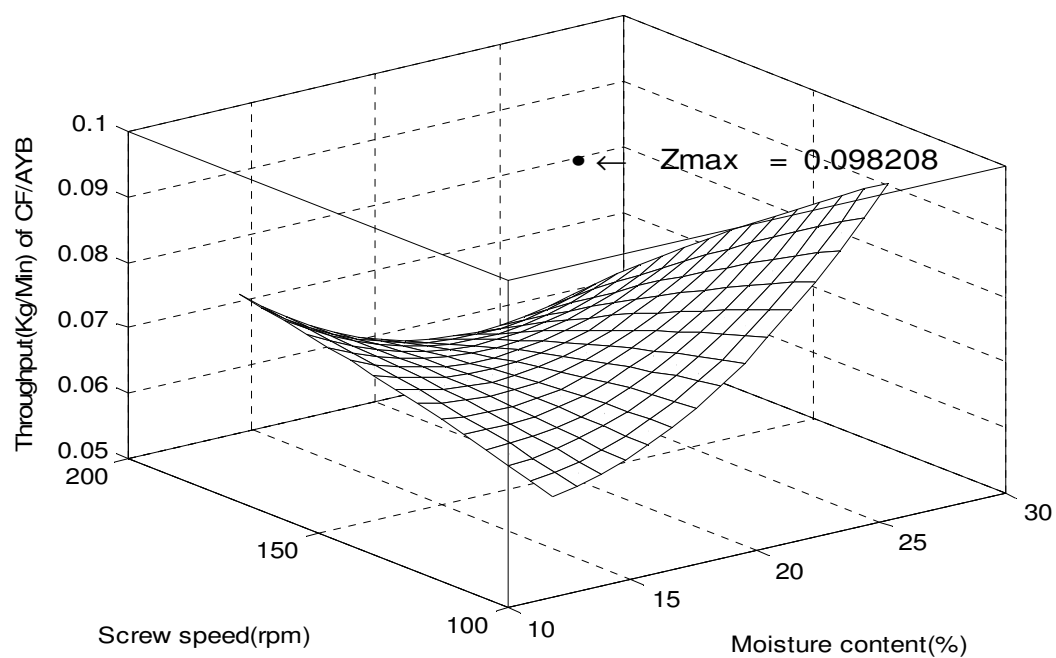


Fig 1: Effect of Screw speed and Moisture content on the Throughput of extruded Cassava/AYB blends.

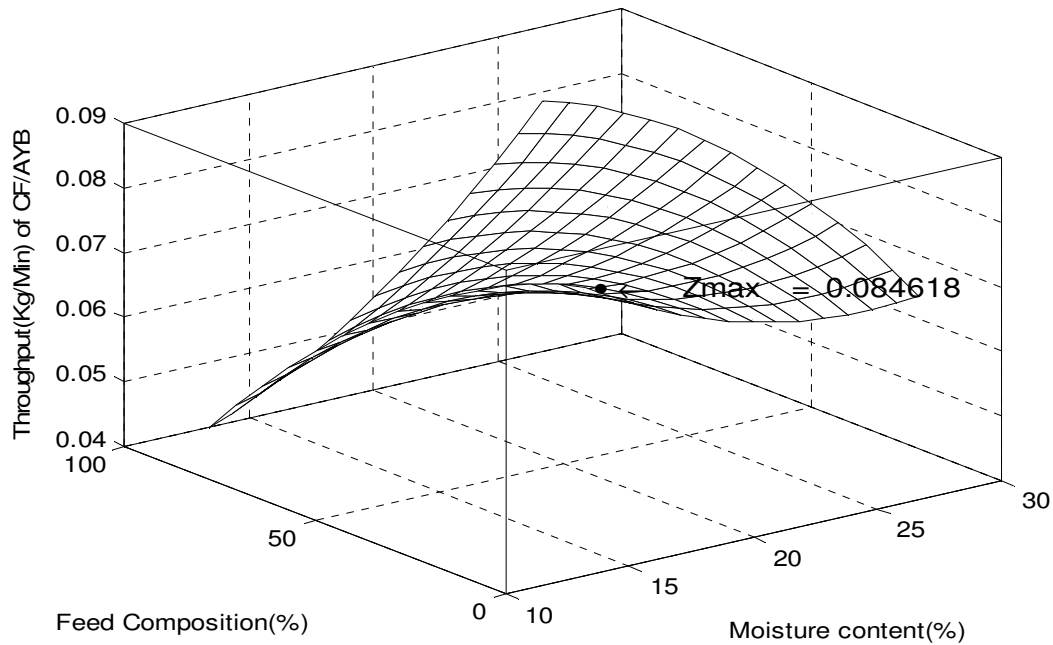


Fig 2: Effect of Moisture content and Feed composition on the Throughput of extruded Cassava/AYB blends.

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

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

(8)

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

(a) Regression Coefficients

Term	Coef	SE Coef	P
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Constant	405.71	42.23	0.01
MC	-10.83	1.91	0.01*
SS	-0.37	0.17	0.04*
FC	-3.38	0.36	0.01*
MC ²	0.12	0.04	0.01*
SS ²	0.01	0.01	0.49
FC ²	0.01	0.01	0.01*
MC*SS	-0.03	0.01	0.01*
MC*FC	0.05	0.01	0.01*
SS*FC	0.01	0.01	0.01*
S = 5.008	R ² = 71.3%	R ² (adj) = 69.3%	

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242

243 (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	0.01
Linear	3	2230.2	2311.57	770.52	30.72	0.01*
Square	3	1492.1	1492.11	497.37	19.83	0.01*
Interaction	3	4077.0	4077.00	1359.00	54.19	0.01*
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				

244 *significant at P=0.05

245

246 The response surface plot in (Fig 3) showed maximum residence time of 59.93s at the
247 critical moisture content value of 13.26% and screw speed of 109.95rpm which were the
248 minimum values used for moisture content and screw speed while the response surface plot

249 in (Fig.4) revealed minimum residence time of 28.63s at the critical moisture content value
250 of 26.73% and screw speed of 125.47rpm.

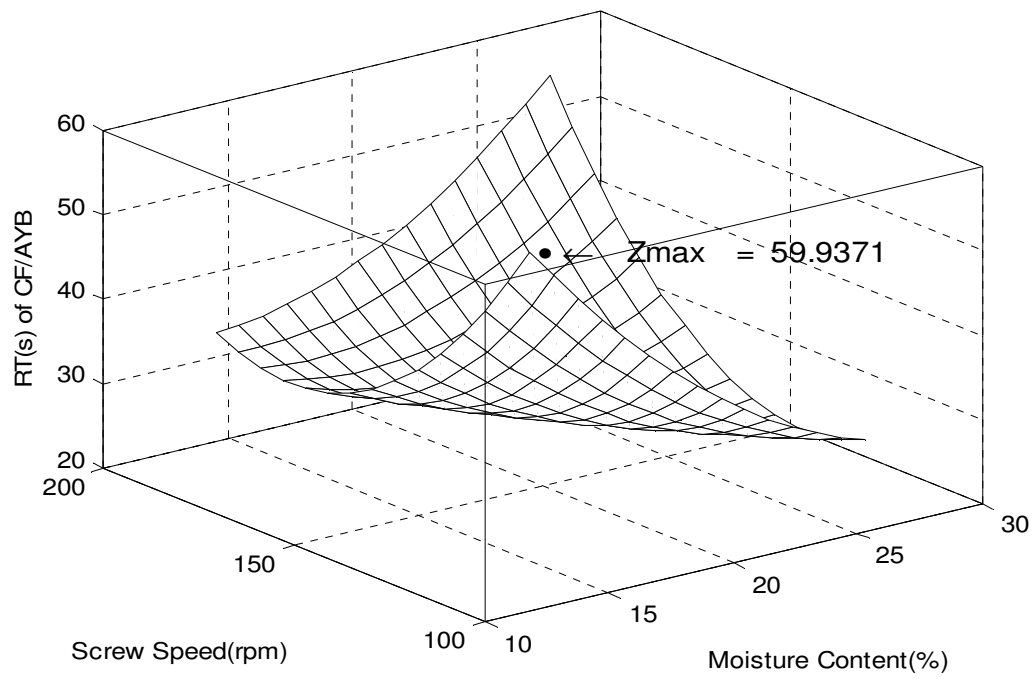
251 The result revealed that RT decreased as the moisture content and screw speed increased.
252 The results were in agreement with the report of some researchers [15] who observed that
253 extrudates spent longer time in the extruder as feed moisture or screw speed decreased
254 from 27% to 15% or 180rpm to 100rpm respectively, thereby increasing the residence time
255 distribution characteristics. Also a report of reduction in average RT in a single screw
256 extruder at increased screw speed was observed [16]. Increase in screw speed enhanced
257 breakthrough time, while a decrease in screw speed enhanced mean RT [17;18]. Increase in
258 moisture content of the feed material led to lubrication of the screw and resultant easier flow
259 of the particles. The ease of discharge of extrudate from the die is a function of the friction
260 imposed.

261 The result revealed that extrusion of AYB was easier and faster than extrusion of cassava
262 products, which may be attributed to the percentage of oil and protein in the AYB and its
263 nature. The feed composition especially the feed oil and protein content and the feed particle
264 size and texture affected the RT. Increase in AYB content resulted to increase in protein
265 content of the feed and subsequent increase in protein-protein interaction at higher levels of
266 protein concentration [19], while the higher the starch content, the more viscous the nature
267 of the mixture during extrusion and the more the difficulty of the exit of the extrudate from the
268 die [20; 21; 18]. It was observed that system parameters (torque and die pressure) are
269 influenced by lipid content of blends [22; 23; 24;25]. In fact, higher lipid fraction in blend with
270 almond or pistachio nut flours involves a gradual decrease of energy necessary to extrude
271 material, thanks to lubricant effect of fat fraction that decreases melt viscosity inside
272 extruder.

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277 Fig 3: Effect of Moisture content and Screw speed on the Residence Time of extruded

278 Cassava/AYB blends.

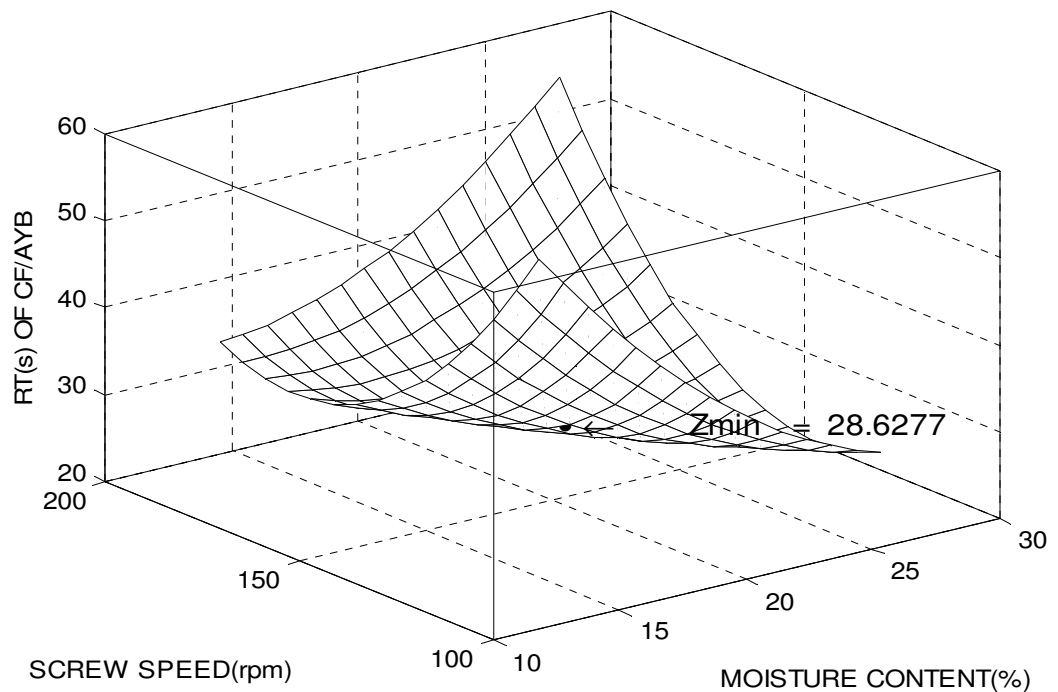


Fig 4: Effect of Screw speed and Moisture content on the Residence Time of extruded Cassava/AYB.

4. CONCLUSION

[This should briefly state the major findings of the study. If you are using copy-paste option then select 'match destination formatting' in paste option OR use 'paste special' option and select 'unformatted Unicode text' option]

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4. CONCLUSION

The study of the residence time is a useful tool in determining the level 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.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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ABBREVIATIONS

d w b dry weight basis

w w b wet weight basis

398	AYB	African yam bean
399	CF	cassava flour
400	SS	screw speed
401	MC	feed moisture content
402	FC	feed composition (CF:AYB)
403	CCD	central composite design
404	RSA	response surface analysis
405	ANOVA	Analysis of variance
406	TP	throughput
407	RT	residence time
408	Y	the response
409	X_1 and x_1	screw speed,
410	X_2 and x_2	moisture content
411	X_3 and x_3	feed composition
412	b_0	intercept
413	$b_1x_1 - b_3x_3$	linear (first order) effect
414	$b_{11}x_1^2 - b_{33}x_3^2$	quadratic (second order) effect
415	$b_{12}x_1x_2 - b_{23}x_2x_3$	cross product (interactive) effect

416 R^2 coefficient of determination

417 P probability value

418 F variance factor

419 DF degree of freedom

420 E error

421