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Influence of Extrusion Variables on the Residence Time and Throughput 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 bench work, performed the statistical analysis, wrote the protocol, and wrote the first draft of the manuscript. Author JNN audited the manuscript. All authors read and approved the final manuscript.

Research Article

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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.
Methodology: 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

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

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

ABBREVIATIONS

d w b: dry weight basis; w w b: wet weight basis; AYB: African yam bean; CF: cassava flour; SS: screw speed; MC: feed moisture content; FC: feed composition (CF:AYB); CCD: central composite design; RSA: response surface analysis; ANOVA: Analysis of variance; TP: throughput; RT: residence time; Y: the response; X_1 and x_1: screw speed; X_2 and x_2: moisture content; X_3 and x_3: feed composition; b_o: intercept; $b_1x_1 – b_3x_3$: linear (first order) effect; $b_{11}x_1^2 – b_3x_3^2$: quadratic (second order) effect; $b_{12}x_1x_2 – b_{23}x_2x_3$: cross product (interactive) effect; R^2: coefficient of determination; P: probability value; F: variance factor; DF: degree of freedom; E: error;

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 [1]. The operating conditions and the rheological properties of the food are the two major factors that influence the nature of the extruded products [2]. In the extruders, the components are mixed, sheared and subjected to elevated temperatures and pressures. So that the dough shows a plastic consistency that favours the expansion of product at the exit of the die. In fact, the sudden drop in pressure at the exit of extruder causes the release of gases entrapped in the product, determining the swelling of extrudates [3]. Many factors affect the expansion of the extrudates: type of plant, screw configuration, moisture content of the dough, residence time, operating pressure, temperature profile of the barrel, screw speed and feed capacity [4]. Also the chemical type of material or ingredient used to produce extrudates could have a considerable effect on expansion degree. The presence of lipids for example leads to a compact structure and involves also technological drawbacks: migration of fatty fraction outside of dough (due to operating temperature and pressure) and, subsequently, percolation of 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 was 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. 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 ± 1ºC) 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:

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

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

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

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); Wx is the weight of water added; w_{CF} and w_{AYB} are the moisture content of cassava flour and AYB respectively.

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**				
	-∝	**-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

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 ± 1ºC).

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 90ºC, 120ºC and 110ºC 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 ± 1ºC 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.

$$(RT = T_i - T_o) \quad (4)$$

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	$-\propto$	0	0	109.95	20	50:50
10	$\propto$	0	0	190.05	20	50:50
11	0	$-\propto$	0	150	13.27	50:50
12	0	$\propto$	0	150	26.73	50:50
13	0	0	$-\propto$	150	20	0.54:99.46
14	0	0	$\propto$	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 which is ratio of cassava/AYB (%)

2.5 Throughput (TP)

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

2.6 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

$$Y = b_o + b_1X_1 + b_2X_2 + b_3X_3 + b_{11}X_1^2 + b_{22}X_2^2 + b_{33}X_3^2 + b_{12}X_1X_2 + b_{13}X_1X_3 + b_{23}X_2X_3 \quad \ldots\ldots\ldots \quad (5)$$

Where Y = the response, X_1= screw speed, X_2=moisture content, X_3= feed composition, b_o=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.

$$Y = \beta_o + \sum_{i=1}^{k}\beta_i x_i + \sum_{i=1}^{k}\beta_{ii} x_i^2 + \sum_{i=1}^{k}\sum_{i=1}^{k}\beta_{ij} x_i x_j + \varepsilon \quad (6)$$

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 polynomial equation after removing the non significant terms becomes:

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

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.

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. 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 rector or for scale up production of commercial extrudated products from blends of cassava/AYB.

Table 3. Response surface regression parameters for influence of process variables on throughput of the extruded blends of cassava/AYB

(a) Regression coefficients

Term	Coefficient	SE Coefficient	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%

(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		
Pure Error	85	0.01	0.01	0.01		
Total	99	0.01				

**significant at P=0.05*

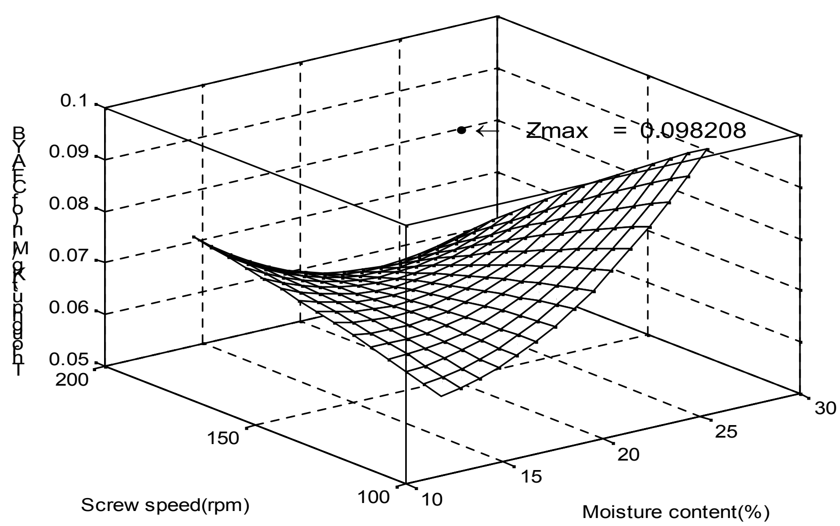

Fig. 1. Effect of screw speed and moisture content on the throughput of extruded cassava/AYB blends

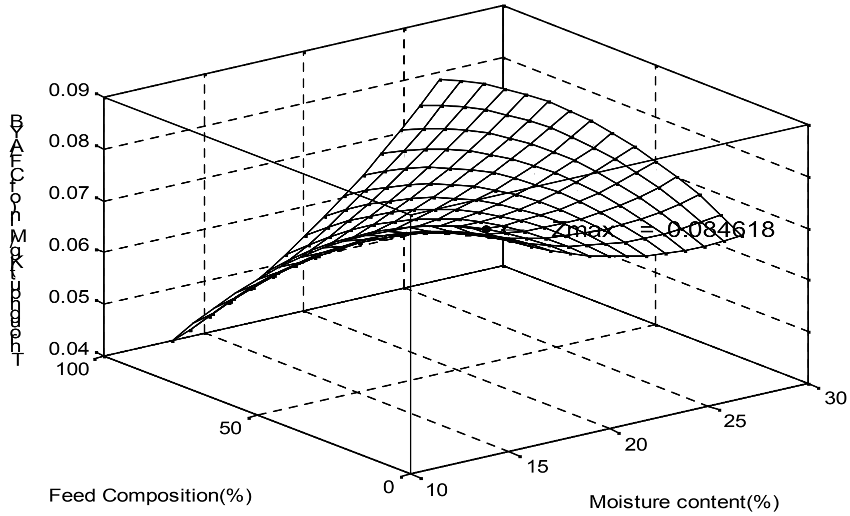

Fig. 2. Effect of moisture content and feed composition on the throughput of extruded cassava/AYB blends

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

$$RTc = 405.71 - 10.829MC - 0.367SS - 3.384FC + 0.124MC^2 + 0.007FC^2 - 0.033MC*SS + 0.048MC*FC + 0.006SS* \quad (8)$$

Table 4. Response surface regression parameters for influence of process variables on residence time of cassava/AYB

(a)Regression coefficients

Term	Coefficient	SE Coefficient	P
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%

(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		
Pure Error	120	0.0	0.00	0.00		
Total	134	10934.4				

**significant at P=0.05*

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 109.95rpm 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 some researchers [15] 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 a report of reduction in average RT in a single screw extruder at increased screw speed was observed [16]. Increase in screw speed enhanced breakthrough time, while a decrease in screw speed enhanced mean RT [17,18]. 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 [19], 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 [20,21,18]. It was observed that system parameters (torque and die pressure) are influenced by lipid content of blends [22,23,24,25]. In fact, higher lipid fraction in blend with almond or pistachio nut flours involves a gradual decrease of energy necessary to extrude material, thanks to lubricant effect of fat fraction that decreases melt viscosity inside extruder.

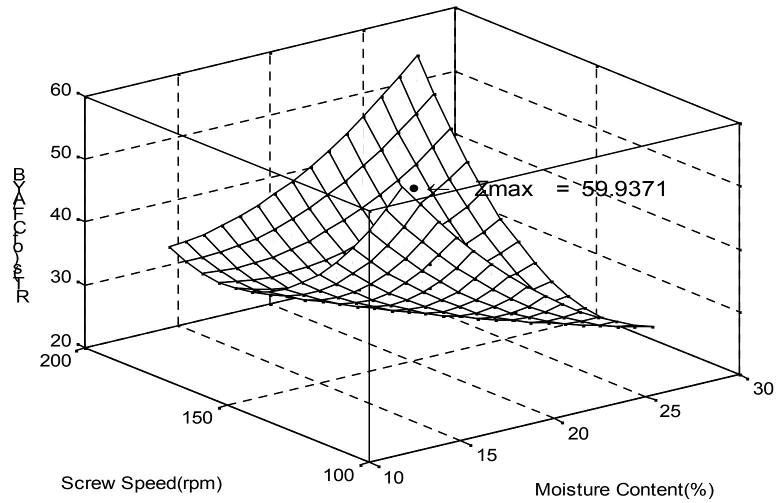

Fig. 3. Effect of moisture content and screw speed on the residence time of extruded cassava/AYB blends

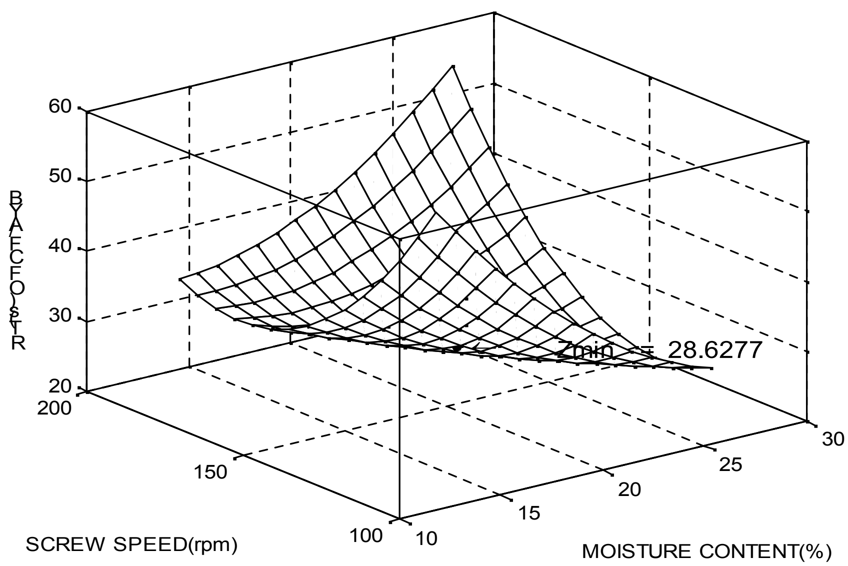

Fig. 4. Effect of screw speed and moisture content on the residence time of extruded cassava/AYB

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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