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ORIGINAL RESEARCH ARTICLE

INFLUENCE OF EXTRUSION PROCESS CONDITIONS ON THE RESIDENCE TIME AND THROUGHPUT OF A TWIN-SCREW EXTRUDER USING FULL FACTORIAL EXPERIMENTAL DESIGN

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ABSTRACT

The effect of extrusion condition on residence time and throughput rate of a twin-screw extruder was investigated using blends of sorghum groundnut and tiger nut in twin-screw extruder SLG65 Model. In this study, a three factor 3-level full factorial experimental design was adopted. The influence of extrusion cooking conditions on both the combine effect and the effect of independent variables were evaluated. The analysis of variance showed that both linear and quadratic were not significant, however, interaction significantly (P<0.05) affect both the residence time and the throughput rate of the extruded. The results revealed that the throughput rate ranged from (0.012-0.040 Kg/s). The highest value was recorded at 100°C barrel temperature, 50:30:20 feed composition for ratios of sorghum groundnut and tiger nut and 18% feed moisture content. While the residence time ranged from (47 - 66.0 S) the highest residence time was obtained at 110°C barrel temperature 50:30:20 ratios of sorghum groundnut and tiger nut and 26 % feed moisture content. The information provided about the residence time and throughput rate of a twin-screw extruder will be used in fabricating an extruder that will be used in producing similar extruded product. The result of the research could be used by intended processors of similar extruded product to explore the possibility of producing similar product by manipulating the processing variables in order to obtain a desired product.

1.0 Introduction

Extrusion cooking is continuous process in which food materials are plasticized to form a fluid melt in the barrel. The high temperature, pressure and shear stress causes the material to be conveyed by a screw. It also forces the material to pass through a die of specific size and formed in to a shape. This shape can be a profile, plate, film, tube, or have any other shape formed from its cross section. The melt can be mixed, densified, plasticized, homogenized, degassed, or chemically altered (reactive extrusion). A subsequent treatment of the semi-finished material before solidification by pressured air or calendaring is also possible. Since the food ingredients (polymer) are completely melted during extrusion and brought into a new form, the extrusion process is a primarily shaping process.

Extrusion is a technology well-known in the plastic industry and now used in food and agro-processing industry. It is referred to as extrusion cooking process. The technology is used in the production of engineered food and special feed. Extrusion cooking is a thermodynamically efficient industrial method of cooking and drying a wide range of foods based on cereals or vegetable proteins or mixtures of both (Carl *et al.*, 1986).

Extrusion of vegetable raw-materials deals with the extrusion of raw-material at barothermal conditions. The shear energy exerted by rotating screw couple with additional heating of the barrel, the food material is heated to its melting point or plasticizing point. Food extruders belong to the family of HTST (High Temperature Short Time) equipment capable of performing cooking task under high temperature and pressure and expel the cooked food within seconds. Exposure of food to high temperature for only a short time has the advantage of restricting unwanted denaturation effects on starches, proteins, amino acids, vitamin and enzymes. Leszek (2005) reported that physical and technological aspect like heat transfer, mass transfer, momentum transfer, residence time and residence time distribution have a strong impact on the food and the feed properties during extrusion cooking and can drastically influence the final product quality.

The food extruder therefore is likened to a continuous flow reactor capable of processing biopolymers and ingredient mixes at relatively high temperature under high pressure and shear forces at relatively low moisture contents. The heating and shearing during the time of extrusion causes series of physical and chemical changes which encompasses starch gelatinisation and dextrinization protein denaturation and cross linking, browning denaturation of vitamins and enzymes and are obviously complex. The resulting properties of the cooked food are a composite of all components, which emerge from the extruder die (Harper, 1981).
There are two classes of extruder (single and twin-screw) based on the number of screws. Single screw extruder consists of a single screw encased in the barrel assembly. The feed material on its way through the open channel of the extruder undergoes a combination of various forces like shearing, mixing, and compression (Zuilichem *et al*., 1999). Single-screw extruders rely on drag flows to move material down the barrel and develop pressure at the die. Additionally, the rotational movement of the screw relative to the barrel wall creates another flow, called the cross-channel flow. This flow, which recirculates material in the channel between the screw flights, does not contribute to the net forward movement of the material. It does, however, contribute to the mixing of the material passing through the extruder. Finally, there is a third type of flow called pressure flow and accounts for the movement of material backwards in a negative direction due to the pressure at the die (Frame, 1994).The twin-screw extruders on the other hand were introduced to the food industry in the 1970s and are now extensively used in food production (Leszek, 2011). In addition to manufacturing foods similar to those produced by single- screw extruders, twin-screw extruders have found a wide application in the food industry due to their better process control and versatility, their flexible design which permitting easy cleaning and rapid product change over together with their ability to handle a wide variety of formulations (Baljit *et al*., 2017).

Twin-screw extruders differ from the single-screw extruder in terms of their processing capability and mechanical characteristics and are largely responsible for the increasing popularity of extrusion processing. The screws in a twin-screw extruder are positioned adjacent to each other and are retained in position by profiled barrel housing, having a horizontal appearance. The position of the screws in relation to one another and their direction of rotation can be used to categorize twin-screw machines. Due to the independent variable screw configuration, twin screw extruders provide greater flexibility of operations to control product characteristics by monitoring time, temperature, pressure, and shear history (Choudhury and Gautam, 1999).
Extrusion is a multi-factor process and because any change in the extrusion variables may affect the quality of the final products, extrusion cooking process are subjected to process optimization to be able to locate optimal process conditions that will produce best or desired product quality or system performance. Several experimental designs including factorial design, central composite design, etc have been used to evaluate process parameters for different types of extruders using different food ingredients. To therefore, fit an approximation model that will

represent the linear and interaction relationships between the process variables, a full factorial approach may be necessary to investigate all possible combinations (Montgomery, 1997).

A factorial experiment is an experimental strategy in which design variables are varied together, instead of one at a time. The lower and upper bounds of each of N (number) of design variables in the optimization problem needs to be defined. The allowable range is then discretized at different levels. If each of the variables is defined at only the lower and upper bounds (two levels), the experimental design is called 2*N* full factorial. Similarly, if the midpoints are included, the design is called 3*N* full factorial.
The objective of this research is to determine the influence of extrusion conditions on the residence time and throughput of a twin-screw extruder using full factorial experimental design approach.

2. MATERIALS AND METHODS

The raw materials used includes sorghum (*Sorghum bicolour L*) red cultivar, groundnut (*Arachis hypogeal L*) red skin, tiger nut (*Cyperus esculentus L*) brown cultivar and granulated red pepper (*Capsicum annum*) were purchased from Jimeta modern market, Yola North Local Government Area of Adamawa State.

2.1 Preparation of Raw Materials

Sorghum, groundnut and tiger nut were sorted manually, cleaned and washed with clean water and allowed to dry in conventional oven at 50°C for 1hour, before roasting at 150°C for 30 min in baking oven. The roasted materials (sorghum and tiger nut) were grounded to flour grinding machine (India Grinding Mill Nissan A2 7hp) and sieved to obtain the particle size of 0.05 mm, while the roasted groundnut was grounded to paste using grinding machine ((India Grinding Mill Nissan A2 7hp). The sorghum, groundnut and tiger nut grits were mixed together in a ratio of 50:20:30, 50:25:25 and 50:30:20 respectively using Horbart mixer (model number A 200) for 10 min. From 1.5 kg of this mixture 2.5% of granulated red pepper (*Capsicum annum*) was added and mixed. The mixture was then packaged and ready for extrusion.

2.3. Experimental Design

In this experiment, second-order factorial design (Eq. 1) was adopted. Factorial designs can be used for fitting second-order models. A second-order model can significantly improve the optimization process when a first order model suffers lack of fit due to interaction between variables and surface curvature. A general second-order model is defined as

$$y = a_0 + \sum_{i=1}^{n} a_i x_i + \sum_{i=1}^{n} a_{ii} x_i^2 + \sum_{i<j}^{n} \sum a_{ij} x_i x_j \qquad (1)$$

Where x_i and x_j are the design variables and *a* are the tuning parameters. The construction of a quadratic response surface model in *N* variables requires the study at three levels so that the tuning parameters can be estimated. Therefore, at least (*N*+1) (*N*+2) /2 function evaluations are necessary. Generally, for a large number of variables, the number of experiments grows exponentially (3*N* for a full factorial) and becomes impractical. A full factorial design typically is used for five or fewer variables. However, in this experiment three factor 3- levels full factorial design was used for the design as shown in Tables 1 and 2 (Yusuf *et al.,* 2017).
A three factor 3-level full factorial experimental design (3x3x3) was used to determine the influence of extrusion conditions on the residence time and throughput of a twin screw extruder during the extrusion of some Nigerian indigenous cereals blended with legume to produce cereal based traditional snack product of northern Nigeria (Dakuwa).The extrusion variables that were considered includes: Feed moisture content (Fm), barrel temperature (Bt)

and feed composition (Fc), at levels each as shown in Tables 1and 2. Thus, making it a 3 (feed moisture) x 3 (barrel temperature) x 3 (feed composition) full factorial design extrusion experiment.

Data generated from the study were statistically analysed using GenStat version 16 and fitted into a quadratic polynomial equation of the type

$$Y = b_o + b_1X_1 + b_2X_2 + b_3X_3 + b_{11}X_{12} + b_{22}X_{22} + b_{33}X_{32} + b_{12}X_1X_2 + b_{13}X_1X_3 + b_{23}X_2X_3 \quad (2)$$

Where: Y = the response, X_1 = barrel temperature, X_2 = feed composition, X_3 = moisture content, 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.

Analysis of variance (ANOVA) was carried out to investigate the influence of operating conditions on the residence time and throughput rate of the extruder using GenStat Software. Three-dimension (3D) histogram was used to predict the influence of independent extrusion variables on the residence time and throughput rate of the extruded snacks. All the graphical presentations were carried out using Microsoft excel.

2.4 Extrusion Processing

The extrusion cooking process was performed using a pilot scale co-rotating twin screw food extrusion cooker **(**SLG65-III Model China) the extruder has a feeder at the top with constant feed rate, it also has a control panel board where the barrel temperature was set. The machine has constant screw speed of 150 rpm and a die diameter of 3mm. The twin screw within the barrel is surrounded with heaters controlled at the control panel board. The grits were alternatively fed into the extruder inlet by volumetric feeder at a feed rate of 0.04 kg/s. The temperature of the three zones of the extruder was controlled by Eurotherm controller and was read on separate control panel board. Extruded samples were collected when the extrusion process parameters reached steady states (Aynadis and Adamu, 2014). Steady state was reached when there was no visible drift in torque and die pressure. Necessary calibration and adjustment of the barrel temperature of the extruder was performed prior to the main extrusion cooking process.

Feed rate and screw speed were constant. The feed composition was varied at 50:20:30, 50:25:25 and 50:30:20 ratios of sorghum, groundnut and tiger nut respectively. The barrel temperature of zone three, which was located just before the die was allowed to operate at different temperatures ranging from 90°C to110°C. By looking at the characteristics of the products from the extrusion, the barrel temperature was selected for the experiment.

The moisture content of the material was adjusted to give moisture contents of 18 %, 22 % and 26 % by using hydration Equation (3).

$$W_a = S_W \times \left(\frac{M - Mo}{100 - M}\right) \quad (3)$$

where:

Wa = Weight of water added (g)

Sw = Sample flour weight (g)

Mo = Original flour moisture content (% weight base)

M = Required dough moisture level (% weight base).

The extrusion experiment was conducted using 3 factor 3 level experiment design (3^3), with 1factor representing extruder barrel temperature, with levels (90°C 100°C 110°C). 2nd factor representing feed composition with levels (50:20:30, 50:25:25, 50:30:20) for sorghum, groundnut and tiger nut respectively, and the 3rd factor representing feed moisture, with levels 18 %, 22% and 26 % as shown in Table 1 and 2. The extruder barrel temperature was set at

90°C and 9samples were run this level, and at 100°C with additional 9samples run at the level. Finally, at 110°C the remaining 9 samples were then run totalling 27 runs. As shown in Table 1 and 2 for experimental design in coded and natural forms. At each case the screw speed remains constant at 150 rpm and the die diameter remain 3 mm. The extruded product was cooled dried and stored in a polythene bag for further analysis.

Table 1: Factors and levels of the 3x3x3 full factorial experimental design

Symbol Factors	Factor Levels	1	2	3
Barrel temperature (°C)	X_1	90	100	110
Feed composition (Sorghum, groundnut, tiger nut)	X_2	50:20:30	50:25:25	50:30:20
Feed moisture (%)	X_3	18	22	26

Table 2. Experimental Design of Extrusion Experiment in their Coded Form

	Independent variables in coded form		
Runs	Bt (X_1) Levels 1 2 3	Fc (X_2) Levels 1 2 3	Fm (X_3) Levels 1 2 3
1	1	3	2
2	1	3	1
3	1	3	3
4	1	2	2
5	1	2	1
6	1	2	3
7	1	1	2
8	1	1	1
9	1	1	3
10	2	2	3
11	2	2	2
12	2	2	1
13	2	3	1
14	2	3	2
15	2	3	3
16	2	1	1
17	2	1	3
18	2	1	2
19	3	2	2
20	3	2	3
21	3	2	1
22	3	1	1
23	3	1	3
24	3	1	2
25	3	3	3
26	3	3	2
27	3	3	1

The experiment was carried out in randomized order. (Bt) = Barrel temperature with levels 1 2 and 3 represents 90 100 & 110 °C, (Fc) = Feed composition with levels 1, 2 and 3 representing 50:20:30, 50:25:25 and 50:30:20 for ratios of sorghum groundnut and tiger nut respectively. (Fm) = Feed moisture with levels 1, 2 and 3 which represent 18 %, 22 % and 26 % respectively.

2.5 Residence Time (RT)

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 colour 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 (Ti) being the total time from the emergency of first colour (To) at the die to disappearance of colour was also noted.

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

2.6 Throughput (TP)

The throughput or mass flow rate was calculated by measuring the mass of the extrudate per unit time taken for the extruded product to come out of the die of the extruder.

$$\text{Throughput rate (Mass flow rate)} = \frac{Weight}{Time} \text{ Kg/s} \quad (5)$$

3. RESULTS AND DISCUSSION

3.1 Residence Time (RT)

Table 3 shows that the least residence timeof47s was recorded at design point 23 ($Bt_3Fc_1Fm_3$) representing 110°C barrel temperature, 50:20:30 feed composition for ratios of sorghum, groundnut and tiger nut and 26% feed moisture content, while the highest residence time of 66 s was recorded at design point 25($Bt_3Fc_3Fm_3$) representing 110 °C barrel temperature, 50:30:20 feed composition for ratios of sorghum groundnut and tiger nut respectively and 26% moisture content. The reason for the low RT in run 23 could be because of high tigernut content in the formulation and a high moisture content that has resulted in speedy passage of the extruded through the die and a low RT. For the high RT observed in run 25

The highest barrel temperature couple with high groundnut content in the formulation and a moisture content might have resulted in the melting and sticking of the ingredients in the barrel thereby increasing the residence of the extruded.

Table 3: Influence of extrusion variables on residence time and throughput rate of a twin-screw extruder.

Sn 123	BtFcFm 123	Residence 123	Time (RT)/s	Throughput	Rate (TR)kg/s
1	1	3	2	51.00	0.027
2	1	3	1	57.67	0.027
3	1	3	3	48.33	0.027
4	1	2	2	48.67	0.037
5	1	2	1	61.67	0.023
6	1	2	3	56.00	0.030
7	1	1	2	54.33	0.030
8	1	1	1	51.67	0.030
9	1	1	3	60.00	0.023
10	2	2	3	58.33	0.033
11	2	2	2	56.67	0.030
12	2	2	1	59.33	0.023
13	2	3	1	50.00	0.040
14	2	3	2	58.33	0.020
15	2	3	3	48.33	0.030
16	2	1	1	58.33	0.027
17	2	1	3	61.58	0.028

18	2	1	2	60.33	0.023
19	3	2	2	61.67	0.027
20	3	2	3	54.00	0.027
21	3	2	1	53.33	0.032
22	3	1	1	58.33	0.025
23	3	1	3	47.33	0.033
24	3	1	2	54.33	0.027
25	3	3	3	66.41	0.012
26	3	3	2	53.33	0.040
27	3	3	1	49.00	0.032

The experiment was carried out in randomized order. (Bt) = Barrel temperature with levels 1 2 and 3 represents 90 100 & 110 °C, (Fc) = Feed composition with levels 1, 2 and 3 representing 50:20:30, 50:25:25 and 50:30:20 for ratios of sorghum groundnut and tiger nut respectively. (Fm) = Feed moisture with levels 1, 2 and 3 which represent 18 %, 22 % and 26 % respectively.

3.1 Residence Time (RT)

The observed results agreed with the finding of Omeire *et al*., (2013) who reported that RT decreased as the moisture content and screw speed increased. The results were in agreement with the report of some researchers (Nwabueze and Iwe, 2012) 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.

The analysis of variance revealed that both linear and quadratic effect were not significant, however interaction effect significantly ($P<0.05$) affects the residence time of the extruded.

The influence of independent variables on residence time of the extruded revealed that increasing barrel temperature from 90°C to 100°C resulted in decreasing the residence time from 60.81 secs to 56.58 secs this is in line with report by SueShan *et al* (2015) that the results showed that an increase in extruder barrel temperature decreased the residence time of the flours in the extruder from 4.11-11.32 min to 2.24-6.76 min. However, increasing the barrel temperature to 110°C increases the residence time to 58.39s it is anticipated that at high temperature the extruded melt and stick to the barrel that result in increasing the residence time as observed. On feed composition also increasing the level of groundnut from 20% to 30% results in increasing the residence time from 58.26 to 59.05 this has to do with melting and sticking of groundnut as a result of high oil content that increases the residence time. On feed moisture content increasing the feed moisture from 18%, 22% and 26% respectively resulted in increasing the residence from 57.27, 58.78, to 59.74 S respectively. Figure 1 represents the 3D Histogram and Figure 2, the 3D Radar projections.

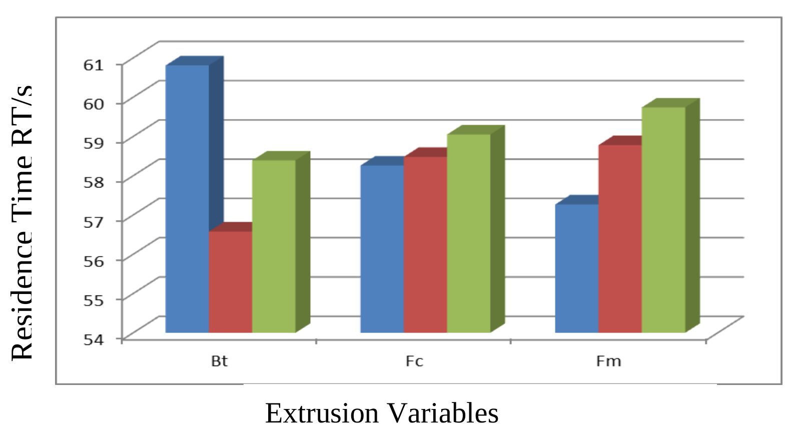

Figure 1: Effect of extrusion variables on residence time RT of extruded

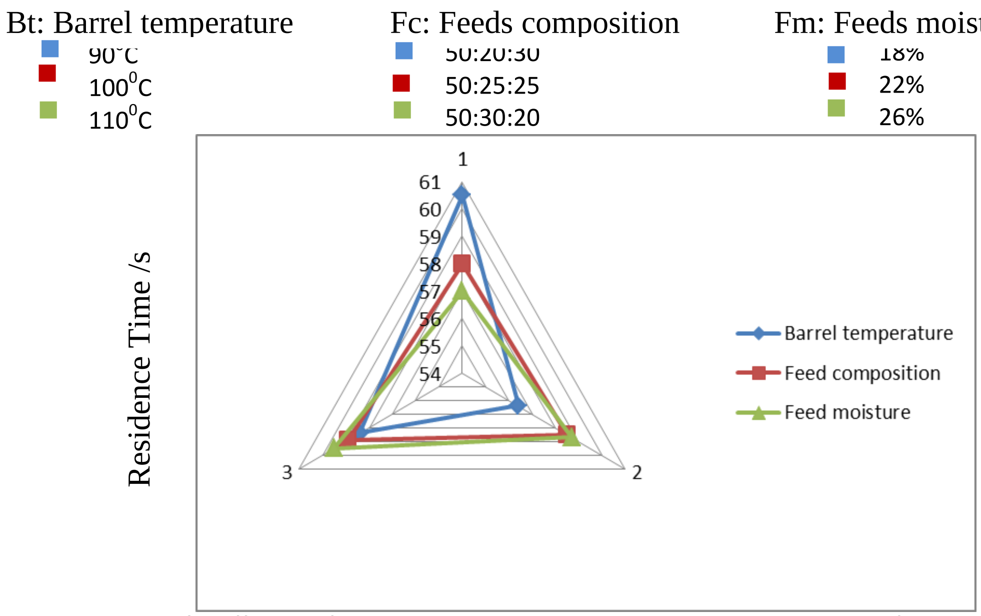

Figure 2: Effects of independent variables on residence time of the extruded (3D Radar Projection)

3.2 Throughput Rate

The least throughput rate of 0.012 Kg/s was recorded at design point 25($Bt_3Fc_3Fm_3$) representing 110°C barrel temperature 50:30:20 feed composition for ratios of sorghum groundnut and tiger nut and 26 % feed moisture content respectively. The least throughput rate recorded at design point 25 could be because of high barrel temperature, high percentage of groundnut that contains high fat and high moisture content. The combination of that result to the melting and sticking of the formulation to the barrel thereby affect the mass flow rate of the melt.

The highest throughput rate of 0.040 kg/s was recorded at design point 13($Bt_2Fc_3Fm_1$) representing 100°C barrel temperature 50:30:20 feed compositions for ratios of sorghum groundnut and tiger nut and 18 % moisture content. The highest throughput rate recorded at design point 13 could be because of low moisture content that reduced the rate of melting and sticking of the formulation in the barrel. That gives the highest mass flow rate of the extruded products. So, the feed composition and the feed moisture content played significant role in ascertaining throughput rate of twin screw extruder of the extruded products since the machine has constant screw speed. This information could be used in the design and construction of extruder for scale up production of extruded products. Analysis of variance showed that linear and quadratic were not significant but interaction significantly ($P<0.05$) affect the throughput rate of the extruded.

The influence of independent variables on the throughput rate of the extruded products were also studied. Increasing the barrel temperature from 90°C to 110°C resulted in increasing the throughput rate from 0.025 to 0.026 Kg/s, the result obtained agreed with the reported literature by Sobowale *et al.* (2016) who found that an increase in barrel temperature increased the mass flow rate to 64.5% of the extrudates significantly ($p<0.05$). On feed composition increasing the percentage of groundnut in the formulation from 20% to 25% resulted in increasing the throughput rate from 0.026 to 0.027 Kg/s, further 30% increase of groundnut content results in decreasing the throughput rate to 0.024 Kg/s and that could be because of high fat content of groundnut, this observed effect is in line with literature reported by

Nwabueze *et al*. (2006) that mass flow rate ranged from 2.99kg/h to 6.72kg/h as feed composition shifted from African bread fruit towards soybean. On feed moisture content increasing the moisture content from 18% to 24% resulted in decreasing the throughput rate from 0.027 to 0.024 as shown in Figure 3 which is 3D Histogram and Figure 4, 3D Radar projections respectively.

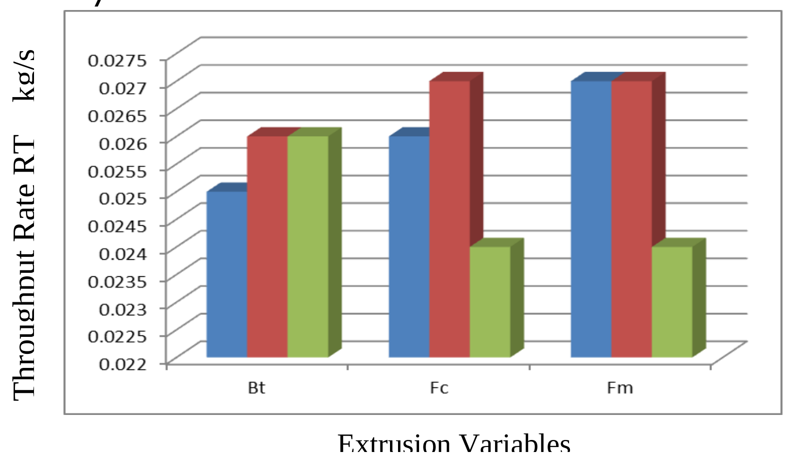

Figure 3: Effect of extrusion variables on throughput rate of extruded

Bt: Barrel temperature
- 90°C
- 100°C
- 110°C

Fc: Feeds composition
- 50:20:30
- 50:25:25
- 50:30:20

Fm: Feeds moisture
- 18%
- 22%
- 26%

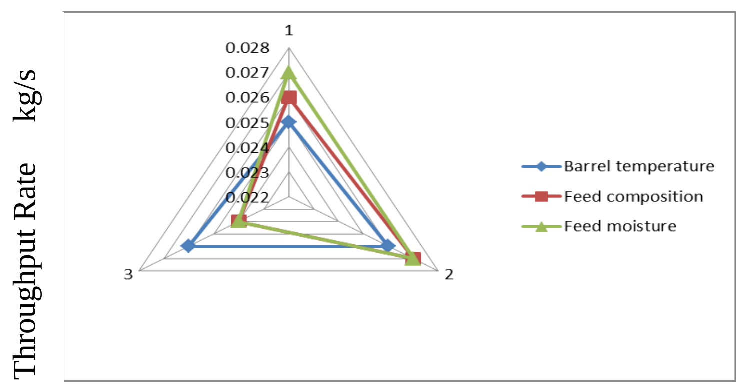

Figure 4: Effects of independent variables on throughput rate of the extruded

(3D Radar Projection)

4. Conlusion

The influence of twin-screw extrusion conditions on residence time and throughput rate of the extruded sorghum-graundnut-tiger nut products were investigated and the result reveals that residence time ranged from 47 to 66s while throughput rate range from 0.012 to 0.040 Kg/s. The analysis of variance showed that both linear and quadratic were not significant, however, interaction significantly ($P<0.05$) affect both the residence time and the throughput rate of the extruded. The knowledge of the optimum values of residence time and throughput rate could be used to design and fabricate an extruder to enhance the production of the extruded foods having similar composition. The research also provides information to some intended processors of Dakuwa through extrusion and similar products on how to manipulate the processing parameters in order to arrive at the desired product quality.

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