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PREDICTIVE EQUATIONS AND RESPONSE SURFACE ANALYSIS FOR GRAIN SORGHUM EXTRUDATE QUALITY

Kehinde Adedeji Adekola.
Department of Agricultural Engineering, Jilin University, Changchun, P.R. China.

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Author(s):
Kehinde Adedeji Adekola.

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Corresponding Author:
Kehinde Adedeji Adekola.
Department of Agricultural Engineering, Jilin University, Changchun, P.R. China.

E-mail: profkola@sina.com

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Abstract

The extrusion and extrudate properties measured include expansion indices (or puff indices), bulk density, residence time, solid density, moisture content, maximum stress, water solubility index (WSI), water absorption index (WAI), extruder output, crispness and color. The ranges of the three variables considered were 100 – 160°C for barrel temperature, 100 - 200rpm for screw speed, and 15 – 25% for feed moisture content (w.b.). The density of extrudate measured varied between 176 and 1100 kg/m3 for the extrusion variables considered. The moisture content of the dry extrudate is between 6 and 7.5 %. From the experimental results, predictive equations were developed to relate the influence of processing parameters on the grain sorghum extrudate quality. Using Matlab computer software for the response surface diagram (RSD), it was discovered that the effect of screw speed on density is negligible. Temperature has a significant impact on the density of the extrudate and it has a curvilinear effect on extrudate density and at high temperature, its quadratic effect dominates. Specific Mechanical Energy (SME) is directly proportional to screw speed. Comparatively, the screw speed has dominating effects on SME while temperature had a small effect. The results of the taste panel on crispness and color show that the product extruded at the conditioned feed moisture content of 20% and barrel temperature of 150°C gave the best crispness and color quality.

Key words: *Extrudate, food extrusion, response surface, sorghum.*

INTRODUCTION

Food extrusion process normally involves application of intensive energy to food ingredients at a pressure within a short period of time to form continuous viscous dough. The laminar flow within the channels on the extrusion screw and extruder die aligns the molecules in the direction of flow to create the crunchy or chewy texture in fabricated food (Godavarti and Karwe, 1997).

A proper understanding of how processing parameters affect the thermo-mechanical, rheological and structural transformation of food polymers into final product will enhance the development of extrusion cooking technology. The early studies of the extrusion processing of food material mainly focused on the effects of physico-chemical parameters of temperature and extrusion moisture content on product properties (Adekola, 1999). The product properties studied then were color, expansion ratio, bulk density and the viscosity of dilute aqueous dispersion.

Later studies show the importance of process variables that control the mechanical history and residence time of materials such as screw speed, feed rate and die geometry (Adekola et al., 1998, Adekola, 2014b). Composition characterization of extrusion cooked starch indicated that they have undergone macromolecular degradation during the extrusion process as reflected in changes in melt rheology and the functional properties of the product such as water solubility, water absorption and dispersion viscosity (Kolani, 1993).

Grain sorghum is produced throughout the tropical, semi tropical and arid regions of the world. Sorghum is a leading cereal grain and it is a mainly used as a principal food in tropical areas of Africa and Asia and often used as raw materials for alcoholic, beverages. United States is the world largest producer of grain sorghum followed by India, Nigeria and Mexico. Grain sorghum is the only food crop that is reported to contain starch in the anatomical section. The endosperm is a storage organ that is comprised of aleurone layer, peripheral, corneous and floury areas. The aleurone contains proteins, ash and oil. The protein of the germ contains high levels of lysine and tryptophan that are excellent in quality (AAGG, 2010).

Influence of extrusion cooking conditions on the product qualities have been generally studied and modeled. The expansion and the shear strength of the products are highly dependent on extrusion cooking conditions. Extruder barrel temperature affected the expansion of corn grits and cornstarch, potato starch and corn germ flour. Lower moisture contents favored the expansion of materials such as corn grit, cornstarch, wheat flour and corn germ flour (Gomez and Aguilera, 1984).

Effects of screw speed, feed moisture, feed rate and product temperature on two processing efficiency variables (percent torque and specific energy input) and extrudate quality (density ratio, hardness ratio and color) has been studied. Increases in the product temperature or feed moisture decreased both the specific energy input and percent torque. A higher screw speed decreased percent torque but increased specific energy input and vice versa for the increase in the feed rate (Hseih *et al*, 1990).

A study was carried out on the influence of process variables on residence time distribution (RTD). RTD is a measure of length of time material spends in an extruder and can influence the extent of both physical and chemical interactions that can occur in the extruder) in the processing of ‘tarhana’, a traditional yogurt- wheat flour mixture used in soup making in Turkey (Ainsworth *et al*, 1997). They observed that increasing feed rate or screw speed, while keeping other operating conditions constant reduce residence time with the feed rate having a more pronounced effect than screw speed. The flow in the extruder approached plug flow as the feed rate increased whereas an increase in the screw speed resulted in the flow approaching mixed flow.

A similar study was carried out using a blend of rice and green gram – a mixture to produce nutritionally balanced traditional products in several South-East Asia countries (Bhattacharya, 1997). It was reported that that a minimum temperature of 150^0C with a screw speed of 100-150 rpm is suitable for developing good expanded product.

Mathematical modeling of effects of extrusion processing parameters on extrudate is becoming more popular for scale up purposes. In the light of this, a mathematical model was proposed to predict the rheological properties of dough (Bhattacharya et al, 1992). The properties are consistency coefficient, flow behavior index and apparent viscosity of blends during extrusion. A simple mathematical model was developed to predict different rheological properties of the dough using data from a tube viscometer. Similarly, two dimensional flow simulations was carried out using ANYSS/FLOTRAN computer software to determine the nature of flow, heat and pressure distribution in the extruder die and to determine the effects of screw speed on process parameters such as temperature, pressure and flow rate in the die (Adekola, 2014).

The studies on effects of process parameters on extrusion efficiency for many grains such as corn, wheat, rice and others are many in literature. However, no known study of the processing parameters for grain sorghum has been reported in literature. In addition, reported work on using response surface analysis and predictive equations to relate the processing parameters to grain sorghum extrudate quality is unknown. Therefore, this paper intends to study the effects of processing parameters such as barrel temperature, screw speed and feed moisture content on extrudate quality for grain sorghum using a twin screw co-rotating food extruder.

EXPERIMENTAL PROCEDURE

Experimental Objectives

To determine the effects of the processing parameters on the extrudate quality using French made Clextral BC45 twin-screw extruder (Figure 1). The three processing parameters considered were screw speed, temperature of barrel at the last section and feed moisture content. The feed material used is white grain sorghum flour.

Experimental Design

Based on the review of available literature, a five-level, three-variable, orthogonal central composite rotatable design was used to design the experiment (Myer, 1971). The variables are the barrel temperature at the last section, screw speed and feed moisture content. These variables were coded at the levels of -1.682, -1, 0, +1 and 1.682. Table 1 shows the level of variables in the experimental plan.

The total number of experiments is 23. The range of the variables (in actual values) was 100 – 160^0C for barrel temperature, 100 - 200 rpm for screw speed, and 15 – 25 % for feed moisture content (w.b.).The response function (y) was related to input variable (X) by a second-degree polynomial in equation below using the method of least squares. The significance of all the terms was determined by the F-test at a probability level 0.01, 0.05 or 0.10. The significance of the correlation coefficient, r was judged at a probability level of 0.01.

$$y = b_0 + \sum_{i=1}^{n} b_i x_i + \sum_{i=1}^{n}\sum_{j=1}^{n} b_{ij} x_i x_j + \varepsilon$$
$$i \le j$$

where n is the number of variable, i and j are integers, b_o, b_i and b_{ij} are the coefficients of the polynomial, ε is the random error.

Machine and Equipment

The experiments carried out in this work made use of the BC45 twin screw co-rotating extruder. It is a modern machine for industrial production. The Clextral Company of France manufactured the extruder. The machine accessories include, the feed mixer, the extrudates

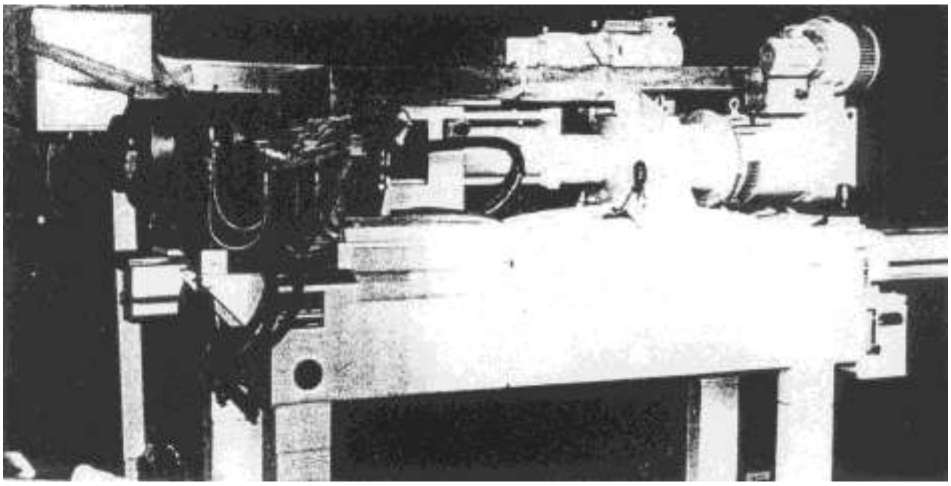

Figure 1: Clextral BC-45 twin-screw extruder

Table 1: Experimental Design for a Three –variable System

Coded level	Actual level		
xj (j = 1,2,3)	Temperature, X1	Screw speed, X2	Feed Moisture, X3
	0C	rpm	%
1.682	160	200	25
1	150	185	23
0	130	150	20
-1	110	115	17
-1.682	100	100	15

cutter, the conveying system and the dryer. The barrel is divided into three sections namely the conveying section, the compression section and the reverse screw section.

The screw sections are divided into seven with the total length screw of 750 mm. From the hopper end, the lengths of the sections are 200, 200, 100, 100, 50, 50 and 50mm respectively. The corresponding screw pitch is 50, 50, 35, 35, 35, 25 and -15mm (because the direction is reversed) respectively (Figure. 2). The die for the BC45 extruder has a single hole for extrusion. Changing the speed of the cutter can produce different shapes and size of extrudates. The width of the slot at the screw end for the dough to flow through to the die is 5mm. The diameter of the tapered die exit hole is 4mm (Adekola, 2014b). The entire system is computer controlled and the values of extrusion parameters can be varied through the control panel.

The advantage of this machine is that it is very efficient in operation, it can work for several hours and the system parameters can be fixed and maintained as desired.

MATERIALS AND METHODS

The white grain sorghum flour used for the experiment was procured from the Extension Unit of North East Agricultural University, Changchun. The proximate analysis (AOAC, 1984) and data given by the Agricultural University Food Research Laboratory for the grain sorghum flour (100g) are as follows: moisture 11.5 g, carbohydrate 70.4g, protein 9.2g, ash 1.2g, fat 3.5g, tannin 0.06g, dietary fiber 4.1g.

The moisture content of the sample was determined by drying in an electric oven at 103^0C until a constant dry weight of the sample is obtained. Sufficient water was added to the flour to bring the moisture content to the desired moisture content for different experimental runs. The samples were then refrigerated in sealed containers. Prior to extrusion, the samples were taken out and allowed to equilibrate with the room temperature.

For the experiments, the extruder throughput was put at 50 kg/h. Calibration of the feed rate and the water addition rate were carried out before each experimental run to ensure accuracy of the feed rate and water rate. These were done by having test runs for two minutes and the samples thus collected are measured. The value is then extrapolated to give the value on hour basis. Each experimental run is replicated thrice and the values reported are the average of the replicates.

The conduction of the experiment involves:

1. Test running the extruder for 30 – 45minutes to ensure smooth operation. At the same time, the barrel is thoroughly washed with water. The test run also allows

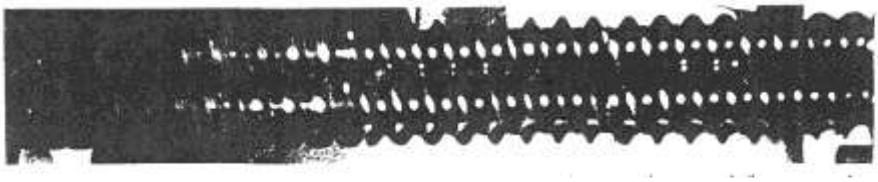

Figure 2: Screw configuration for the BC45 Clextral extruder used for experiments

the extruder barrel to be heated to the designed temperatures for extrusion.
2. Loading the feed hopper with pre-conditioned feed material.
3. Feeding the extruder with the feed material and water.
4. The remaining process depends on the peculiarity of the experiment.
5. Finally, the extrudates are collected for post-extrusion treatment and analysis.

Extrusion and Extrudate Properties Measurements

Expansion indices (or puff indices)

The determination of longitudinal (or axial) LEI, radial (or sectional) SEI, and volumetric, VEI, indices are done according to the following expression (Alvarez-Martinez *et al,* 1988, Adekola, 2014b). Ten replicates were made to get the average.

For LEI, it is defined as :

$$LEI = \frac{V_e}{V_d} \quad 1$$

and

$$V_d = \frac{\dot{Q}_d}{S_d} \; V_d = \frac{\dot{Q}_d}{S_d} \quad 2$$

where V_e is the extrudate velocity after expansion, V_d is the extrudate velocity in the die, S_d is the cross sectional area of the die, and $\dot{Q}_d$ is the volumetric flow rate through the die. A mass balance equation for the extruder will give the expression:

$$\dot{m}_d = \left[\frac{1-\dot{M}_e}{1-\dot{M}_d}\right]\dot{m}_e \quad 3$$

where $\dot{m}_d$ is the mass flow rate of the dough entering the die, $\dot{m}_e$ is the mass flow rate of the extrudate, M_d and M_e are the dough and extrudate moisture content (w.b.). Also:

$$\dot{Q}_d = \frac{\dot{m}_d}{\rho_d} \quad 4$$

Substituting eqn. 2, 3 and 4 into eqn. 1

$$LEI = \frac{V_e \rho_d S_d}{\dot{m}_e}\left[\frac{1-M_d}{1-M_e}\right] \quad 5$$

where ρ_d is the density of the dough behind the die, which is often assumed as constant was 1250 kg/m^3. The actual velocity of the extrudate from the die, V_e is

$$V_e = L_{se}\dot{m}_e \quad 6$$

where L_{se} is the specific length of the extrudate defined as the length of the extrudate per unit mass (m/g). By substituting eqn. 6 into eqn. 5 and knowing that $S_d = \pi D_d / 4$ gives :

$$LEI = \left[\frac{\pi D_d^2}{4}\right] L_{se}\rho_d \left[\frac{1-M_d}{1-M_e}\right] \quad 7$$

where D_d is the diameter of the die.
The sectional expansion index is given as :

$$SEI = \frac{S_e}{S_d} = \frac{\left(\pi D_e^2/4\right)}{\left(\pi D_d^2/4\right)} = \left[\frac{D_e}{D_d}\right]^2 \quad 8$$

where S_e is the cross-sectional area of the extrudate, D_e is the diameter of extrudate.

The diameters of the extrudates were measured with a venier caliper. The volumetric expansion index is given as the product of the sectional and longitudinal expansion indices.

$$VEI = SEI \cdot LEI \quad 9$$

Bulk Density

Bulk densities of the extrudate were obtained by volumetric displacement procedure (Hwang and Hayakawa, 1980) using glass beads as the filler medium.

Glass beads with diameters ranging from 100 - 105 μm were used. Nine pieces of extrudate, each 3.5cm long were used. Three layers of extrudates completely covered with glass beads were made in sequence. The bulk density of extrudate was calculated using the equation

$$\rho_{ex} = \frac{W_{ex}}{W_{gb}} \rho_{gb} \qquad 10$$

where W_{ex} is the weight of the extrudate, W_{gb} is the weight of the glass beads, ρ_{gb} is the density of the glass beads. The density of the glass beads was determined using the volume displacement method. The density of the glass beads was calculated using the equation

$$\rho_{gb} = \frac{W_{gb}}{V_{gb}} \qquad 11$$

where V_{gb} is the volume of the glass beads. Three replicates give the average value for bulk density.

The alternative method used was to calculate the mean diameter and weight of the extrudate per unit length. It was assumed the extrudate are perfectly cylindrical in shape. The volume of the cylindrical shape was then calculated. The weights per unit length (about 5cm) were measured by using sensitive electronic weighing machine. Prior to measurement, extrudate samples were allowed to equilibrate with the laboratory atmosphere for about six days to bring them to uniform moisture content. Ten replicates of the diameter and weight give the mean values reported. The results obtained from these methods are comparable.

Residence Time

The residence time of the dough in the extruder are determined by introducing colored dye tracer in the feed at the entrance of the extruder. The residence time is determined by timing the time it takes the colored dough to be extruded. Different screw speeds were used during the experiment. Fifteen replicates gave the average value.

Solid density

The solid densities of the extrudate were determined by using air comparism multi-volume pycnometer. The extrudate samples were grounded to pass through #80 mesh sieve and placed in pycnometer cup. Masses were recorded and sample volumes were determined. The densities were calculated as mass per unit volume

Moisture content

The moisture content of the extrudate were determined by drying them in a conventional air-vacuum oven at 103^0C until a constant weight is obtained.

Specific Mechanical Energy (SME)

The total specific mechanical energy input during extrusion is estimated by using the following expression (Hseih, et al, 1990; Hwang and Hayakawa, 1980).

$$SME = \frac{\text{rpm of screw (run)}}{\text{rpm of screw (rated)}} \times \frac{\text{\% torque (run)}}{100} \times \frac{\text{motor power (rated)}}{\text{production capacity}} \; 6.12$$

Maximum stress, σ_m

The maximum stress of the dry extrudate was obtained as the ratio of maximum force applied during shearing and the corresponding cross sectional area of the extrudate. The maximum force during shearing was obtained using Instron Universal Testing machine. The machine was operated at the crosshead speed of 500mm/min. Five replicates gives the average value reported.

Water-solubility index (WSI) and Water-absorption index (WAI)

The water-solubility indexes and water-absorption indexes were measured by using the method prescribed (Anderson et al, 1969). The extrudate were milled to particle size of between 200 and 250 μm . A 2.0g sample was dispersed in 20.0g of distilled water. The resulting lumps were broken using a glass rod. The mixture was then stirred for about 20min., and afterwards rinsed into centrifuged tubes made up to 30g. The TGL – 16 centrifuge model was used. It was operated at the speed of 1600rpm for about 15min. The supernatant was decanted to determine its solids content and the sediment was weighed. The indices for WSI and WAI are:

$$WSI (\%) = \frac{\text{weight of dissolved solids in supernatant}}{\text{weight of dry solids}} \times 100$$

$$WAI = \frac{\text{weight of sediment}}{\text{weight of dry solids}}$$

Three replicates of the measurement were carried out.

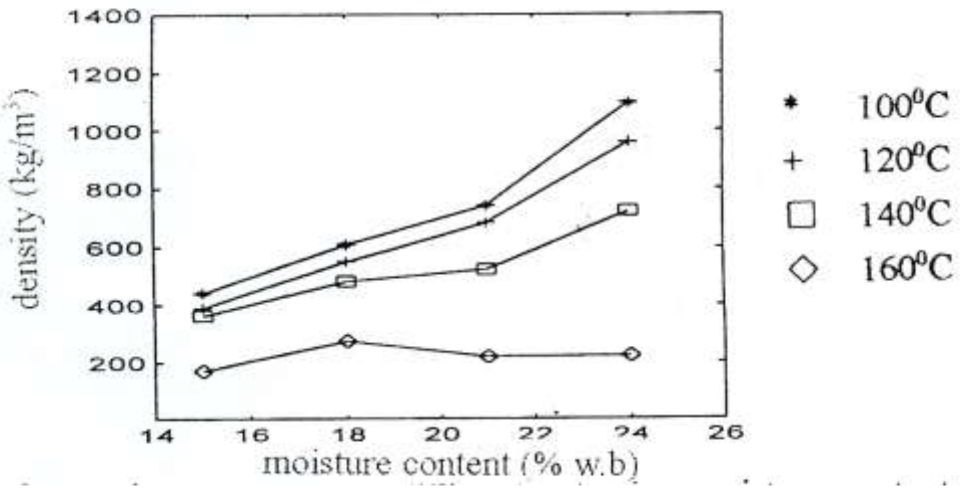

Figure 3: Density of extrudate at different extrusion moisture contents and barrel temperatures

Extruder Output

The extruder output for each die were determined by collecting the sample of the extrudate for 5min and weighing after drying at 60^0C for 24h. The extrudate mass flow rate on dry basis was calculated (kg/h). On the volumetric basis, the flow rate was calculated by dividing the mass flow rate by the extrudate solid density.

Crispness and Color

A taste panel of five was set up to evaluate the quality of the extrudate in terms of crispness and color of the extrudate. The scoring is from 1 to 10 with the highest quality being 10 while the lowest quality is 1 in that descending order.

RESULTS AND DISCUSSION

The three processing parameters considered were: screw speeds (100 – 200rpm), temperature of barrel at the last section (100 – 160^0C) and conditioned feed moisture content (15 – 24%). The feed material used is white grain sorghum flour.

The density of extrudate varied between 176 and 1100kg/m^3 for the extrusion variables considered. The moisture content of the dry extrudate is between 6 and 7.5 %. Figure. 3 shows the density of the extrudates at different extrusion moisture contents and barrel temperature. The figure shows an increasing density with increasing moisture content. It is noticeable that there is a sharp change in the density over a small temperature increment such as 20^0C increment from 140^0C to 160^0C. These changes may be due to the complete disruption of the molecular structure of corn particle and gelatinization of their starch granules.

Low density was obtained with higher temperature above 140^0C. Low density is desirable in extrusion, because it enhances the extrudate quality. Conversely, high-density value was obtained for low barrel temperature (100 – 120^0C). At low temperature, the corn particles are not completely disrupted and a poorly expanded and uncooked extrudate is produced with high density.

From the response surface diagram (RSD) (Figure 4), the effect of screw speed on density is negligible at constant feed rate. Also, there is a drastic reduction in density with an increase in temperature from 100 to 145^0C, above 145^0C, the rate of decrease in density became rather small. This strongly suggests that temperature has a significant impart on the density of the extrudate. Based on the experimental results, and using regression analysis, an equation was developed to show the relationship between density of extrudate and processing factors of the barrel temperature and the screw speed below:

$$\rho = 7799.3256 - 98.3798X_1 - 0.9314X_2 + 0.3160X_1^2 + 0.0008X_1X_2 + 0.0025X_2^2$$

where ρ is the density of the extrudate (kgm^{-3}), X_1 is the barrel temperature (^{0}C), X_2 is the screw speed (rpm). The correlation coefficient at probability level of 0.01 for the polynomial is 0.986

The regression equation shows the dominance of the first order over the second order. The barrel temperature shows a negative linear effect whereas its quadratic effect was positive. This suggests that temperature has a curvilinear effect on extrudate density and at high temperature, its quadratic effect dominates.

The water-solubility and water-absorption results are depicted in Figure 5 and 6 respectively. The solubility

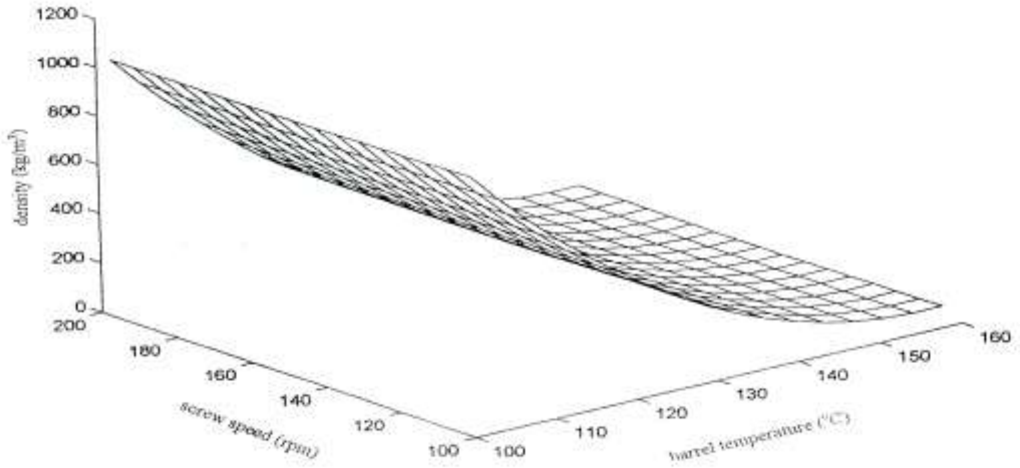

Figure 4: Response surface diagram for extrudate density at different screw speeds and barrel temperatures.

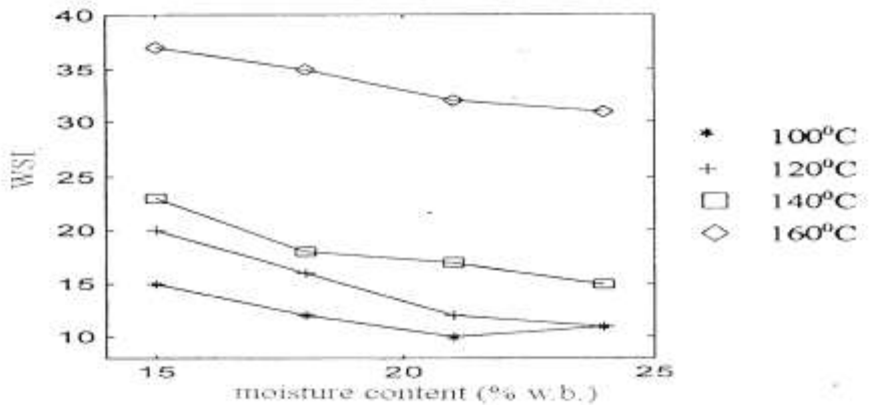

Figure 5: Water-solubility index of extrudates at different extrusion moisture contents and barrel temperatures.

tends to increase linearly with increase in temperature and decreases linearly with increase in moisture content. At temperature below 150^{0}C, the WAI recorded is between 5.1 and 5.3 and to a large extent is independent of the extrusion moisture content. However, at the temperature higher than 150^{0}C, there is a sharp increase in WAI to a value of 6.0 and above.

The total specific mechanical energy (SME) varied between 475 and 1000kJ/kg. SME is directly proportional to screw speed. At low screw speed, the SME is low and vice-versa (Figure. 7). Comparatively, the screw speed has dominating effects on SME while temperature had a small effect. The regression equation below relates barrel temperature (X_1), and screw speed (X_2) to SME.

$$SME = 606.372 - 2.856X_1 - 0.037X_2 + 0.017X_1^2 - 0.006X_1X_2 + 0.005X_2^2$$

where X_1 is the barrel temperature, X_2 is the screw speed. The correlation coefficient, r at probability level of 0.01 for the polynomial equation is 0.974

The results of the taste panel on crispness and color show that the product extruded at the conditioned feed moisture content of 20% and barrel temperature of 150^{0}C gave the best crispness and color quality.

CONCLUSIONS

Food extrusion is a technology that will continue to

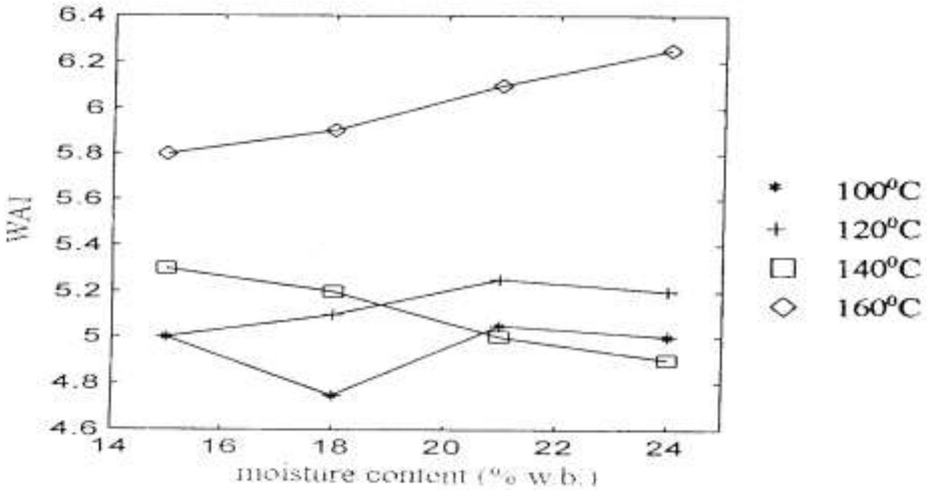

Figure 6: Water-absorption index of extrudate at different extrusion moisture contents and barrel temperatures

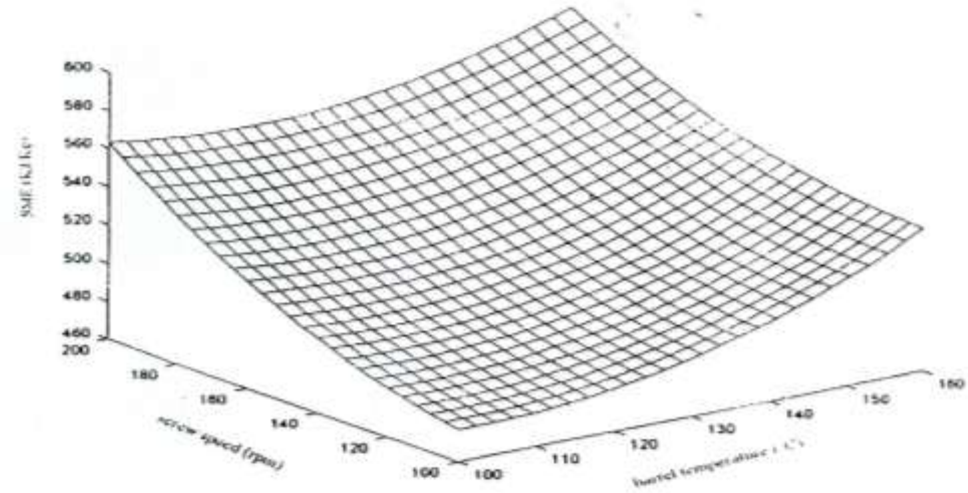

Figure 7: Response surface diagram for SME during extrusion of yellow corn flour at different barrel temperatures and screw speeds

receive research and application attention worldwide. The potentials and benefits of the technology is immense and yet to be fully tapped. This paper developed prediction models to predict the effects of process parameters such as barrel temperature, screw speed and feed moisture contents on extrudate quality for grain sorghum which is being reported for the first time in literature.

In food extrusion operation, screw speed, barrel temperature and feed moisture content significantly affect the quality of extrudate and extrusion operation. Increase in feed moisture content causes increase in density of extruded products. At low barrel temperature, the value of extrudate density is high. The effect of screw speed is negligible on density. The water solubility index (WSI) increases linearly with increase in temperature and decreases linearly with increase in moisture content. Screw speed has dominating effects on SME while temperature has small effects. At low screw speed, SME is low and vice-versa. The results from this work on grain sorghum extrusion will spur further research in this new area and contribute to the development of knowledge.

Further studies are needed on other parameters affecting extrusion of grain sorghum. Understanding the mechanical and rheological properties of food dough will help in obtaining data and information necessary for research and development purposes. Focus should also be in the area of co-extrusion of sorghum with other cereals and additives to provide more nutritional snacks.

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