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Performance Evaluation and modeling of a Poundo-yam Single Screw Extruder

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Abstract— A low speed single screw poundo-yam extruder was designed, constructed and mathematically modeled. The performance evaluation of the extruder was carried out using slices of white yam (*Dioscorea rotundata*) and the effects of screw speed (x_1) and quantity of added water (x_2) on the extrudate throughput (y_0) and residence time (y_r) were investigated using a 3^2 full factorial design, with 3 levels of screw speed (13,15, and 17 rpm) and 3 levels of quantity of added water (300, 400, and 500 mls/kg of tuber slices). Empirical relationships were developed to established the effects of screw speeds and level of added water on the throughput and extrudate residence time within the barrel. Results indicated that screw speed and the amount of added water affect the extrusion process, the extrudate output, and the extrudate residence time. Both factors have positive influences on extrudate output. However, screw speed is more influential than quantity of added water. On the effects of the two factors on extrudate residence time, it was found that both factors have negative influences. However, quantity of added water has less negative influence than screw speed.

Index Terms— Poundo-yam, Single Screw, Extruder, 3^2 Full factorial design, Screw speed, Quantity of added water, Extrudate throughput, Extrudate residence time.

1 Introduction

The greater part of the world's yam crop is consumed as poundo-yam. Poundo-yam is a very popular food product all over Africa. ([3, 2] IITA Annual Report 1997, 1998; http://www.africanfoods.co.uk/yam.html). However, the conventional process for making poundo-yam is tedious and energy demanding.

Since poundo-yam has so much prestige and is the most popular way of eating yam, concerted research efforts must be made at improving and/or replacing the dominant traditional and current batch poundo-yam processing methods.

The main objective of this project was to develop a single screw poundo-yam extruder and investigate its performance as well as model the extrusion throughput and residence time.

The subject of extrusion is now of major importance in food processing and are being applied in so many diverse operations ([7,4] Riaz *et al.*, 1996; Mian, 2000). The ability of extrusion systems to carry out a series of unit operations simultaneously and continuously, combined with the ability to produce shapes not easily formed with other production methods, have led to extensive use of extrusion in the food industry ([3] Mian, 2000).

1.1 Description of the Poundo-yam Extruder

The 25:1 length-to-diameter ratio (L/D) low speed single screw poundo-yam extruder comprises of a 2148mm long high strength stainless steels barrel within which a stainless steel screw of 1898mm nominal length and 65mm nominal diameter is rotatably mounted. The extruder is made up of three geometrical sections: feed/solid conveying section, with a deep uniform channel; the tapered transition/kneading section, with a uniformly decreasing channel depth; and the shallow uniform channel metering/mixing/texturizing section ([5] Olorunsogo, 2013).

The extruder screw, sometimes called the "auger," has the following basic functions:

1. The screw is the means for transporting ingredients inside the extruder and the principal means for shearing the product. Material transport through the extruder is accomplished by the screw geometry and screw motion. The screw conveys material by viscous drag against the barrel. The direction of flow through the barrels is from the left to the right.
2. Mix the extrudate produce into a homogeneous mass.
3. Apply the constant pressure required to force the material out of the extruder.

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These functions are generally achieved at the different sections of the extrusion screw as the material progresses along the barrel.

The poundo-yam extruder employs a main drive motor to supply power to the extruder screw, which provides the force necessary to push the raw material through the barrel. The extruder screw receives power from a 10hp, 1440rpm electric motor via a drive reducing gear assembly (Model EU 40), and a multiple-grooved pulley/V-belt drive system. The gearbox reduces the motor's speed and, in turn, multiplies the available torque from the motor in order to produce sufficient power to convey, knead, mix, texturize and pump the extrudate ([5] Olorunsogo, 2013).

1.2 Operational Principles of the Poundo-yam Extruder

Pre-cooked yam tuber slices are fed into the hopper at one end of the barrel and enter the barrel assembly through the feed throat into the feeding/conveying section. At first, the initial material is crushed at the feeding zone and pushed to the conveying zone. The rotating screw (turning at a low speed) forces the crushed tuber slices forward in the barrel. As the solid matter is pushed along the barrel by the rotating screw it undergoes further crushing, compression, shearing, melting, kneading, mixing, texturization, and plasticization. Shear occurs as the compressed product is wiped against the wall of the extruder barrel and fed forward against the back pressure created by the breaker plate. By the respective design of the screw in the transitional section, the crushed material undergoes some degree of compression and shearing. At the end of the transitional section the homogeneous mass enters the metering/kneading/texturizing section where further melting and mixing of the solid mass takes place. This section is characterized by a positive, forward-transport screw configuration. The texturization, plasticization, and blending of the extrudate occurs in this section. The viscoelastic dough then is formed into moulds and pushed out through the extruder chute.

In the extrusion process there are three resistances to overcome: the rubbing of solid particles (pre-cooked yam slices) against the barrel grooves and wall and each other in the first few turns of the screw; the adhesion of the extrudate to the barrel wall; and resistance to flow within the extrudate as it is pushed forward. The screw is pushing extrudate out of the extruder under high pressure where Newton's law states that there must be an equal reaction of the screw driving backwards in the machine. The screw does not move in an axial direction, although it is turning rapidly in the cross direction around the circumference, the forces on it must be balanced in that direction. So, the axial forces on the screw must be balanced; and if it is pushing forward with great force on the extrudate it must be pushing backward on something with equal force. In this case, it is pushing on a bearing behind the feed entry called the thrust bearing. The high load thrust bearing is used to support the rearward force on the screw.

2 MATERIALS AND METHODS

There are many variables that affect food extruder performance, it's production throughput and residence time. These variables may be divided into two main groups.

The first group includes geometrical variables which are related directly to the machine design and the production process. These variables that must be specified to cut a screw and they include the screw diameter, the total length, the flighted length, the flight clearance, the helix angle of the screw, the length or number of turns in each geometrical section (feed, tapered, and metering), the lead, the feed depth, the metering depth, and the flight width, In addition, one must specify the shank and the bearing diameters, the keyway, the feed pocket, the front and rear radii, and the nose cone ([1]Harold et al., 2005). This group of variables are difficult to change during experimentation process; for this reason they are usually taken as constants related to this specific machine.

The second group of variables, the optimization variables, consists of the variables related to the properties/ constituents of the feed stock (e.g. the moisture content of the feedstock mixture and the binder content) and the operational parameters such as screw speed.

2.1 Performance Evaluation of Poundo-Yam Extruder

Two main parameters were considered for the performance of the extruder: screw speed and the quantity of added water. Extrudate throughput and residence time were the dependent variables.

2.1.1 Extrusion Experiments

2.1.2 Preparation of Raw Materials

Batches of seven hundred grams of peeled, washed yam slices from *Dioscorea rotundata* were precooked to a temperature of $120\,^{0}C$ in 500 mls of water for 20 min.

2.1.3 Conduct of the Extrusion Experiment

Pre-cooked tuber slices were introduced into the feeding section of the extruder through the hopper. Screw speeds and quantity of added water were varied based on the design matrix. While operating, measured quantity of water at ambient temperature was injected into the extruder via feeding hopper. Varying screw speed and the amount of added water, the extrudate throughput and residence time were recorded. Each sample of the pounded yam was wrapped in nylon foil immediately after preparation to prevent drying of the surface and kept in a box for about 25 min to keep it warm prior to quality evaluation.

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2.2 Experimental design

Prior to the conduct of the extrusion experiment, an appropriate experimental design matrix was selected. The relationships between the performance indexes of the extruder and the two critical factors were determined on the basis of experimental design.

A two-variable, three level full factorial design with three replicates was used. The use of three levels implies the possibility of nonlinear relationships between the two factors and the response. The full regression equation contains linear terms, quadratic terms, cubic terms and all interactions between the factors ([6] Olorunsogo)

2.3 Extrusion Experiments

The effect of screw speed $\left(x_1\right)$ and quantity of added water $\left(x_2\right)$ on the extrudate throughput $\left(y_o\right)$ and residence time $\left(y_r\right)$ was investigated using a 3^2 full factorial design, with 3 levels of screw speed (13, 15, and 17 rpm) and 3 levels of quantity of added water (300, 400, and500 mls/kg of tuber slices).

3 RESULTS

The poundo-yam extruder was designed, constructed with locally available materials and evaluated. The design concept was based on extrusion principle.

3.1 The Result of the Extrusion Experiments

Preliminary traditional pounding experiment conducted shows that 300 to 500 mls of added water/kg of cooked yam tuber slices from *D. rotundata* gives product with adequate consistency. This suggested the choice of the level of added water for the 3^2 full factorial experimental design matrix. The factors and their coded levels are presented in Tables 1.

The 3^2 full factorial design matrix is shown in Tables 2. The extrudate output experimental data (kg/min) and extrudate residence time (min.) are presented in Tables 3 and 4.

3.2 Data Analysis and Modeling of Extrusion Processing

3^2 full factorial design/multivariate regression analyses were used in relating the variables. Tables 5 and 6 present the summary of the estimated effects, the confidence interval, and the calculated t-values for both extrudate output experimental data and the extrudate residence time experimental data.

The mean experimental values, the fitted values, the residuals, and the squares of the residuals for both extrudate output experimental data and the extrudate residence time experimental data are presented in Tables 7 and 8. The complete analysis of variance (ANOVA) for both extrudate output data and the extrudate residence time experimental data are presented in Tables 9 and 10.

Table 1: Factors and their coded levels, the 3^2 full factorial design matrix and extrudate output experimental data (kg/min).

Level of factors	Code	Independent variables levels x_1	Independent variables levels x_2
Low level	-1	13 rpm	300 mls/kg
Medium level	0	15 rpm	400 mls/kg
High level	+1	17 rpm	500 mls/kg
Variation Interval	Δx_i	2 rpm	100 mls/kg

Table 2: The 3^2 full factorial design matrix

Run No	x_0	x_1	x_2	x_{12}	x_1^2	x_2^2	$x_1^2 x_2$	$x_1 x_2^2$	x_1^3	x_2^3
1	+1	-1	-1	+1	+1	+1	-1	-1	-1	-1
2	+1	0	-1	0	- 2	+1	+2	0	0	-1
3	+1	+1	-1	-1	+1	+1	-1	+1	+1	-1
4	+1	-1	0	0	+1	- 2	0	+2	-1	0
5	+1	0	0	- 2	- 2	- 2	0	0	0	0
6	+1	+1	0	0	+1	- 2	0	- 2	+1	0
7	+1	-1	+1	-1	+1	+1	+1	-1	-1	+1
8	+1	0	+1	0	- 2	+1	- 2	0	0	+1
9	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1

Note: $x_1 = Screw\ Speed\ \left(rpm\right)$,

$x_2 = Quantity\ of\ added\ water$ $\left(mls/kg \text{ of tuber slices}\right)$.

$y_O = Extrudate\ Output\ \left(kg/\text{min}\right)$

Table 3: The extrudate output experimental data (kg/min)

Replicates y_{O_1}	Replicates y_{O_2}	Replicates y_{O_3}	Mean $\bar{y}_O$	Temp. ^0C
0.069	0.071	0.070	0.070	60
0.081	0.080	0.082	0.081	65
0.092	0.091	0.093	0.092	70
0.073	0.074	0.075	0.074	62
0.085	0.084	0.086	0.085	63
0.095	0.096	0.094	0.095	68
0.075	0.074	0.076	0.075	61
0.089	0.087	0.088	0.088	63
0.098	0.099	0.097	0.098	65

The fitted models for extrudate output and extrudate residence time are given in Equations (1) and (2), respectively.

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Table 4: The extrudate residence time experimental data (min)

Replicates y_{R_1}	y_{R_2}	y_{R_3}	Mean $\bar{y}_R$	Temp. ^0C
4.45	4.47	4.46	4.46	60
3.54	3.55	3.53	3.54	65
3.22	3.23	3.24	3.23	70
4.40	4.42	4.41	4.41	62
3.38	3.39	3.37	3.38	63
3.22	3.20	3.21	3.21	68
4.37	4.36	4.38	4.37	61
3.32	3.31	3.30	3.31	63
2.55	2.57	2.56	2.56	65

Note: $y_O = Extrudate\ Output\ (kg/\min)$

$$\left.\begin{aligned}\hat{y}_O &= 0.0842 + 0.0073x_1 + 0.0020x_2 - 0.0188x_{12} - 0.0004x_1^2 \\ &- 0.0004x_2^2 + 0.0073x_1^3 + 0.0020x_2^3\end{aligned}\right\} \quad (1)$$

$$\left.\begin{aligned}\hat{y}_R &= 3.6078 - 0.4711x_1 - 0.1100x_2 - 0.8156x_{12} \\ &+ 0.1978x_1^2 - 0.0589x_2^2 - 0.0333x_1^2x_2 \\ &- 0.0711x_1x_2^2 - 0.4711x_1^3 - 0.1100x_2^3\end{aligned}\right\} \quad (2)$$

4 DISCUSSIONS

From the extrudate output fitted model, it can be seen that both screw speed and quantity of added water (with regression coefficients $b_1 = 0.0073$ and $b_2 = 0.0020$) have positive influences on extrudate output. However, screw speed has more positive influence than quantity of added water. Using the fitted model to generate the predicted values (at the coded levels of the independent factors), the processing condition of experiment 5 (i.e., 15 rpm screw speed and 400 mls of added water /kg of cooked yam tuber slices) gave the highest extrudate output with value $\hat{y}_{O5} = 0.1236$ kg/min.

From the response surface function, it is possible to determine values of the factors $(x_1 \text{ and } x_2)$ needed to give a specified extrudate output $\hat{y}_O$. On the other hand, given a specified extrudate output and either of the factors $(x_1 \text{ or } x_2)$ the value of the other factor can be determined. For instance, equation (1) above can be rearranged to give:

$$x_1 = \frac{\hat{y}_O - \left(\begin{aligned}&0.0842 + 0.0020x_2 - 0.0188x_{12} - 0.0004x_1^2 - 0.0004x_2^2 \\ &+0.0073x_1^3 + 0.0020x_2^3\end{aligned}\right)}{0.0073}$$

where, $\hat{y}_O$ and x_2 are specified, the coefficients are known, and the only unknown is x_1.

or,

$$x_2 = \frac{\hat{y}_O - \left(\begin{aligned}&0.0842 + 0.0073x_1 - 0.0188x_{12} - 0.0004x_1^2 \\ &- 0.0004x_2^2 + 0.0073x_1^3 + 0.0020x_2^3\end{aligned}\right)}{0.0020}$$

Table 5: The summary of the estimated effects, confidence interval, and the calculated t-values for extrudate output experimental data

Regression Coefficient	Estimated Effect	Confidence interval	t-value
b_0	0.0842	0.0842 ± 0.0003337	437.6315
b_1	0.0073	0.0073 ± 0.0003337	38.1051
b_2	0.0020	0.0020 ± 0.0003337	10.3923
b_{12}	-0.0188	0.0188 ± 0.0003337	97.5722
b_{11}	-0.0004	0.0004 ± 0.0003337	2.3094
b_{22}	-0.0004	0.0004 ± 0.0003337	2.3094
b_{112}	-0.0003	0.0003 ± 0.0003337	1.7321*
b_{122}	0.0003	0.0003 ± 0.0003337	1.7321*
b_{111}	0.0073	0.0073 ± 0.0003337	38.1051
b_{222}	0.0020	0.0020 ± 0.0003337	10.3923

Table 6: The summary of the estimated effects, confidence interval, and the calculated t-values for extrudate residence time

Regression Coefficient	Estimated Effect	Confidence interval	t-value
b_0	3.6078	3.6078 ± 0.0033	1899
b_1	- 0.4711	- 0.4711 ± 0.0033	248
b_2	- 0.1100	- 0.1100 ± 0.0033	58
b_{12}	- 0.8156	- 0.8156 ± 0.0033	429
b_{11}	0.1978	0.1978 ± 0.0033	104
b_{22}	- 0.0589	- 0.0589 ± 0.0033	31
b_{112}	- 0.0333	- 0.0333 ± 0.0033	17.5
b_{122}	- 0.0711	- 0.0711 ± 0.0033	37.4
b_{111}	- 0.4711	- 0.4711 ± 0.0033	248
b_{222}	- 0.1100	- 0.1100 ± 0.0033	58

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where, $\hat{y}_O$ and x_1 are specified, the coefficients are known, and the only unknown is x_2.

By using these transformed expressions, combinations of x_1 and x_2 can be obtained, which will give any specified value of $\hat{y}_O$.

Table 7: The mean experimental values, the fitted values, the residuals, and the squares of the residuals for extrudate output experimental data

$\bar{y}_O$	$\hat{y}_O$	e	e^2
0.0700	0.0459	0.0241	0.0006
0.0810	0.0807	0.0003	9×10^{-8}
0.0920	0.1128	-0.0208	0.00043
0.0740	0.0700	0.0040	0.000016
0.0850	0.1236	-0.0386	0.0015
0.0950	0.0993	-0.0043	0.000018
0.0750	0.0914	-0.0164	0.0003
0.0880	0.0887	-0.0007	0.0000005
0.0980	0.0832	0.0148	0.0002

Table 8: The mean experimental values, the fitted values, the residuals, and the squares of the residuals for extrudate residence time experimental data

$\bar{y}_R$	$\hat{y}_R$	e	e^2
4.46	4.0933	0.3667	0.1344
3.54	3.3733	0.1667	0.0278
3.23	3.8400	-0.6100	0.3721
4.41	4.8656	-0.4556	0.2075
3.38	4.9611	-1.5811	2.4999
3.21	2.9811	0.2289	0.0524
4.37	5.2844	-0.9144	0.8362
3.31	2.9333	0.3767	0.1419
2.56	1.7689	0.7911	0.6259

Table 9: The complete analysis of variance (ANOVA) for extrudate output data

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F - Value
b_1	0.0002	1	0.0002	4[µ]
b_2	0.000012	1	0.000012	0.24[µ]
b_{12}	0.0011	1	0.0011	22
b_{11}	5.93×10^{-7}	1	5.93×10^{-7}	0.01186[µ]
b_{22}	5.93×10^{-7}	1	5.93×10^{-7}	0.01186[µ]
b_{112}	3.33×10^{-7}	1	3.33×10^{-7}	0.00666[*µ]
b_{122}	3.33×10^{-7}	1	3.33×10^{-7}	0.00666[*µ]
b_{111}	0.0002	1	0.0002	4[µ]
b_{222}	0.000012	1	0.000012	0.24[µ]
Error	0.0009	18	0.00005	
Total		27		

[*] Statistically insignificant coefficients

[µ] Coefficients does not contribute significantly to the regression.

Table10: The complete analysis of variance (ANOVA) for extrudate residence time experimental data

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F - Value
b_1	0.6658	1	0.6658	1.7269[*]
b_2	0.0363	1	0.0363	0.0941[*]
b_{12}	1.9954	1	1.9954	5.1753
b_{11}	0.1173	1	0.1173	0.3044[*]
b_{22}	0.0104	1	0.0104	1.7269[*]
b_{112}	0.0033	1	0.0033	0.0086[*]
b_{122}	0.0152	1	0.0152	0.0393[*]
b_{111}	0.6658	1	0.6658	1.7269[*]
b_{222}	0.0363	1	0.0363	0.0941[*]
Error	6.9402	18	0.3856	
Total		27		

[*] Statistically insignificant coefficients

5 CONCLUSION

A poundo-yam extruder was designed, constructed and evaluated. The design concept was based on extrusion principle, and the materials of construction were locally sourced. Effects of screw speed (x_1) and quantity of added water (x_2) on the extrudate throughput (y_0) and residence time (y_r) were established using a 3^2 full factorial design.

REFERENCES

[1] Harold F. Giles , John R.Wagner and Eldridge M. Mount. (2005). Extrusion: The Definitive Processing Guide and Handbook. William Andrew, Inc., 13 Eaton Avenue, Norwich, NY 13815. Pages 13-32, 53-62, 79-81.

[2] http://www.africanfoods.co.uk/yam.html.Pounded yam

[3] IITA Annual Report 1997, 1998

[4] Mian N.R. 2000. Extruders in Food Applications. Taylor & Francis Group USA. Pp. 2-4, 167-170, 205-214.

[5] Olorunsogo, S.T. (2013): Development and Evaluation of the Performance of a Poundo-Yam Extruder. Ph.D Dissertation, Federal University of Agriculture, Abeokuta. Nigeria.

[6] Olorunsogo, S. T. (1998). Determination of Quality Factor Levels for Enhanced Shelf-life of Selected Fruit Juices Under Non-Refrigrated Storage Conditions. M.Eng. Thesis, Department of Agricultural and Bioresources Engineering, School of Engineering and Engineering Technology, Federal University of Technology, Minna, Nigeria.

[7] Riaz, M. N., Lusas, E. W. and Din, G.M. 1996. Application of extrusion technology in food industries. Pakistan Journal of Food Sciences, 6(3-4): 85-88.

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