American Journal of Engineering Research (AJER) 2020
American Journal of Engineering Research (AJER)
e-ISSN: 2320-0847 p-ISSN : 2320-0936
Volume-9, Issue-8, pp-75-82
www.ajer.org
Research Paper Open Access

Modelling the Performance of a Roasting Machine

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ABSTRACT: *The performance of a roasting machine was studied. The aim was to model the roaster using design expert 8.0.7.1. Maize grain (Suwan-1-SR-Y) was used. The factors selected were speed, moisture content and temperature and the parameters of evaluation include roasting capacity, roasting efficiency, conveyance efficiency and mechanical damage. The statistical analysis conducted showed that the model was significant ($p<0.01$) for all the evaluation parameters. The coefficient of determination (R^2) of the effect of combined factors on the evaluation parameters of the roaster were high, 83, 60 and 89 for roasting efficiency, conveyance efficiency and mechanical damage respectively. The regression equations relating the factors and parameters of evaluation showed linear, two factor interaction and quadratic regression. The predicted roasting equations showed that all the variation in factors of speed, temperature and moisture content contributed to the total variation in the roaster performance parameter (R^2 = 0.3409 to 0.8925).*

KEYWORDS: *Performance, Roaster, Evaluation, Modelling, Suwan.*

Date of Submission: 27-07-2020 Date of acceptance: 11-08-2020

I. INTRODUCTION

Roasting is the process by which a product, basically agricultural products, is exposed to dry heat in an oven or over a fire for the purpose of removing moisture and cooking of the products to make it suitable for consumption, it involves the application of dry heat to legume seeds using a hot pan or dryer at a temperature of 150ºC to 200ºC for short time, depending on the legume or the recipe to be made. Roasting produces a better product as far as protein quality is concerned than one produced by common wet cooking under pressure. There are several food crops which need roasting before consumption, these include coffee, peanut and other legumes.

Maize (*Zea mays L.)* or "corn" as it is known in some part of the world, is the main cereal grain as measured by production but ranks third as a staple food, after wheat and rice [1]and [2]. Yellow dent maize contains 61% starch, 8% protein, 11.2% fiber, 3.8% corn oil and 16% moisture [3]. When maize is roasted it gives a palatable taste and love to be consumed by both young and old. Maize roasting has been a popular postharvest operation that produce highly commercial agricultural products and also preserve the products for longer self-life [4].

The performance of roasters for different cereal crops were examined at various parameters and the characteristics of corn were studied [5], [6], [7], [8] and [9]. Some researchers had worked on the properties, compositions and effect of roasting corn at different temperatures [10], [11], [12], [13], [14], [15], [16], [17] and [18]. The moisture content and harvesting stage of the corn, moisture distribution due to drying have been described [19] and [20]. The principles of heat transfer are based on the energy sources and mode of transportation heat to the system [21]. The effect of roasting on chemical composition of maize was studied [22]. In handling and processing of agricultural products roasting plays a vital and important role.

Roasting as applied to maize must have started some hundred years ago [23]. Traditionally, the maize with its husk is thrown directly into a fire and removed after the husk may have been burned. But with modern technology, roasting is done by placing the maize on a glowing charcoal with the maize itself separated from the charcoal by a metal grill. The maize to be roasted is placed on a glowing charcoal and then turned occasionally to allow even distribution of heat. The charcoal is placed inside a tray and a metal grill is placed on top of the tray mainly to separate the maize to be roasted and the charcoal. To maintain the charcoal from glowing, a hand fan is used to blow air which support combustion. The faster the hand fan blow the faster the air current, the faster the rate of combustion and the rate of heat transfer from the charcoal to the maize. By convection, the heat is transferred to the maize on the metal grill. The process highlighted becomes strenuous as the operator gets tired out with time before the maize is completely roasted. The direct contact and exposure of the human body to direct heat emitted from the charcoal may have some damaging effect on the skin and some organ in the body.

Starting from 1864, roasting equipment/roasters manufactured on an industrial scale for the first time in the world. The pressure cooking of black beans for 10 to 30 min at 121ºC improved the utilization of black bean, as compared to raw beans. Also, that the in vitro digestibility of navy beans was improved by mild heat treatment. Excessive heating reduced the nutritive value of beans due to the destruction or in activation of certain essential amino acids [24]. A Multi-Purpose Roasting Machine was developed. The multipurpose roasting machine was made up of roasting chamber, heating chamber, two blowers, and driving (power transmission) mechanism. The machine was used to test the following food items: yam, maize and plantain[25]. Amaize roaster with treadle drive blower.Roasting was done by means of the treadle drive mechanism which drives the blower that support combustion of the charcoal in the tray and by manually turning the maize in the sample within the grill on the charcoal tray [26].

Quality Protein Maize (dent/flint) contains nearly twice as much usable protein as other maize grown in the tropics. The utilization potential is high especially for breakfast menu, livestock industries and for lactating/nursing mothers, pregnant women and weaning babies will also find it beneficial. Other additional attributes include high *Ogi* yield, better storability and higher crude fibre [27]. Although Quality Protein Maize (dent/flint) has been introduced to farmers, but there is need to generate data for engineers and food scientist who are involve in designing processing machine and processing methods for maize in order to ensure food security and enhance development of mini industries. Therefore, this study aims at filling the knowledge gap in the designing process for maize milling with respect to the use of Quality Protein Maize. This report will present data on the use of Quality Protein Maize for food processing and the processing parameter that favours the use of the roaster designed at the Federal University of Technology Akure, Nigeria.

II. MATERIALS AND METHODS

The maize grain, Figure 1 was obtained from the Institute of Agricultural Research and Training, Moor Plantation, Ibadan. Suwan-1-SR-Y, yellow grain, dent/flint in texture with yield potential of about 4.0 Mt/ha was used for the experimentation[27]. The factors selected were moisture content on dry basis (MC_{db}) using a microprocessor grain moisture meter, machine operating time (t) with stopwatch, shaft speed (v) of the roaster using photo contact tachometer (DT-2236B), temperature (T) which was regulated by temperature controller. The initial moisture content and final moisture content of maize were determined for maize at a pass for the roasting machine.

Fig.1. Maize (SUWAN-1-SR-Y variety)

Determination of some engineering properties

The following engineering properties were observed and measured- length (mm), width (mm), thickness (mm), effective diameter (mm), sphericity, surface area (mm^2), moisture content (%), mass of 1000 grains (kg), bulk density (kg/mm^3), true density (kg/mm^3), porosity, repose (^{o}), coefficients of friction and Stress-strain properties. Therefore, these properties constitute an essential engineering data in the design of the roasting machine and in analyzing the performance and the efficiency of the machine.

Description of the Roasting machine

The roaster, Figure 2 comprises of a double cylindrical body insulated which housed the electric heating elements in-between, a spiral conveyor within the circular axis of the cylindrical body that convey the material to be roasted from the inlet to the outlet, and the conveyor also stirs the material along in order to prevent heat concentration on one surface of the material. The roaster is provided with an electrical control switch to select the roasting temperature and the roaster is powered by a speed reduction gear electric motor [28].

Fig.2. The roaster

Experimentation

Five speeds, 6.6, 12.8, 19, 24 and 30 rpm, three moisture levels, 20, 15.8 and 9.5% and three temperatures 70, 100 and 150^{o}C were chosen. The selections were based on the past literatures. A known weight of maize sample was passed through the hopper into the roaster and exit after roasting. The initial moisture content of the grains was recorded before introducing it into the roaster and the temperature of the inside of the roasting chamber was also recorded. The final weight and moisture of the product was measure. Part of the product that was left over in the roaster was retrieved and the weight was measured in order to check for the conveyance efficiency of the roaster. Each experiment was replicated five times. The roasting capacity (*RC*), conveyance efficiency (*CE*), roasting efficiency (*RE*), and Mechanical damage (*MD*) will be determined from the following formula.

Roasting Capacity *RC*, $$RC = \frac{m_r}{t} \quad (1)$$

Where m_r is the final mass of collected product (kg) and t is the roasting time (min)

Conveyance Efficiency *CE* is calculated from the relationship similar to the formula used by [29] to calculate the conveyance efficiency of water.

Conveyance Efficiency *CE*, $$CE = \frac{m_c}{m_c + m_w} 100\% \quad (2)$$

Where m_w and m_c equal to the mass of maize retained within the roasting chamber and collected at the outlet respectively.

Roasting Efficiency *RE*, $$RE = \frac{m_r}{m_r + m_u} x100\% \quad (3)$$

Where $m_r$is the mass of roasted product, $m_u$is the mass of unroasted maize

Mechanical Damage *MD*, $$MD = \frac{m_t}{m_c} x100\% \quad (4)$$

Where m_t is the mass of burnt maize and $m_c$is the mass of product.

Data analysis

The statistical analyses of the observed performance parameters were estimated. Effects of the factors on the evaluation parameter for different treatments were investigated using Analysis of Variance (ANOVA). The statistical package used for data analysis was Design Expert version 8.0.7.1.

III. RESULTS AND DISCURSIONS

Engineering properties of the Suwan maize

Engineering properties of the maize plays an important role in the determination of the evaluation parameters of the roaster. Table 1 present the result of the physical properties of the maize while Table 2 shows the Stress-strain properties. The dimension characteristics and the surface area governs the clearance between the roasting unit and the screw conveyor. The clearance facilitates the movement of grains within the chamber and prevent burnt to the grain during conveyor movement. The 1000 grain weight was used for the theoretical determination of the grain's effective diameter and the angle of repose used to determine the hopper inclination. The bulk and true densities, porosity, coefficients of friction influence the pressures exerted on hopper walls and flow through the roasting chamber. The stress-strain properties were used for further processing of the maize after roasting. The maximum, minimum, mean and standard deviation were presented (Table 1). The maximum values for length, width and thickness were 12.65, 11.05 and 6.89 mm respectively.

Table 1: Descriptive statistics of the physical properties of the Suwan maize

Properties	N	Maximum	Minimum	Mean
Length (mm)	100	12.65	7.11	9.99±1.18
Width (mm)	100	11.05	5.04	7.97±1.09
Thickness (mm)	100	6.89	3.20	4.60±0.85
Effective Diameter (mm)	100	9.23	5.91	7.13±0.56
Sphericity	100	0.90	0.61	0.72±0.07
Surface Area (mm^2)	100	267.50	109.70	160.69±25.89
Moisture Content (%)	10	12.90	10.80	11.26±0.61
Mass of 1000 grains (kg)	10	0.32	0.30	0.3089±0.01
Bulk Density (kg/mm^3)	10	757.20	739.25	749.70±6.18
True Density (kg/mm^3)	10	1290.00	1250.00	1274.0±20.66
Porosity	10	42.69	39.76	41.14±0.92
Repose (^{o})	10	43.81	38.66	42.04±1.65
Coefficients of friction:				
Smooth Glass	10	0.38	0.58	0.46±0.06
Rough Glass	10	0.31	0.38	0.33±0.03
Galvanize Steel	10	0.47	0.55	0.51±0.03
Stainless Steel	10	0.38	0.47	0.43±0.03
Plywood	10	0.49	0.58	0.52±0.03

N = number of replication

Table 2: Stress-strain properties for lengthwise and breadthwise orientation of the Suwan maize

Properties	Lengthwise Mean	Breadthwise Mean
Maximum Compressive stress (MPa)	0.4507±0.1810	0.6243±0.5616
Compressive strain at Maximum Compressive stress (mm/mm)	0.1218±0.0446	0.0666±0.0200
Energy at Maximum Compressive stress (J)	0.0513±0.0329	0.0321±0.0298
Compressive load at Maximum Compressive stress (N)	96.5310±38.7568	133.7011±120.2641
Compressive extension at Maximum Compressive stress (mm)	1.1548±0.4227	0.6313±0.1898
Compressive stress at Break (Standard) (MPa)	0.2248±0.3819	0.4001±0.6986
Compressive load at Break (Standard) (N)	48.1340±81.7925	85.6894±149.6056
Compressive strain at Break (Standard) (mm/mm)	0.1296±0.0425	0.0812±0.0262
Load at Maximum Compressive stress (N)	-96.5310±38.7568	-133.7011±120.2641
Extension at Maximum Compressive stress (mm)	-1.1548±0.4227	-0.6313±0.1898
Compressive extension at Break (Standard) (mm)	1.2289±0.4030	0.7702±0.2483
Load at Break (Standard) (N)	-48.1340±81.7925	-85.6894±149.6056
Extension at Break (Standard) (mm)	-1.2289±0.4030	-0.7702±0.2483
Energy at Break (Standard) (J)	0.0566±0.0343	0.0421±0.0374
Compressive stress at Yield (Zero Slope) (MPa)	0.2108±0.2466	0.2796±0.3841
Compressive load at Yield (Zero Slope) (N)	45.1502±52.8186	59.8857±82.2543

Effect of factors on the evaluation parameters

Effects of speed, temperature and moisture content on RC

There was a significant ($p \leq 0.05$) influence of the linear factors of conveyor speed, and moisture content of maize on the roasting capacity. It was observed from the statistical analysis that both conveyor speed and temperature had significant ($p \leq 0.05$) linear effect on the model, equation 5 (Table 3). The model could explain about 34.09% of the variations in roasting capacity. As shown in the response plots (Figure 3a-c), both speed, and temperature had significant effects on the roasting capacity of the Suwan-1-SR-Y maize. 2FI factor was obtained when ART/98/SW06-OB-W was used to evaluated the roaster. The predicted model and the response surfaces confirmed that speed of auger had a positive influence on roasting capacity [28].

$$RC = 15.77191 + 0.67588S - 0.049583T - 0.28621\,Mc \quad (R^2 = 0.3409). \tag{5}$$

Table 3. ANOVA for linear model of RC

Source	Sum of Squares	Df	Mean Square	F Value	p-value Prob > F	
Model	671.75	3	223.92	7.07	0.0006	Significant
A-Speed	600.16	1	600.16	18.95	< 0.0001	
B-Temp	299.68	1	299.68	9.46	0.0037	
C-MC	68.64	1	68.64	2.17	0.1486	
Residual	1298.59	41	31.67			
Cor Total	1970.33	44				

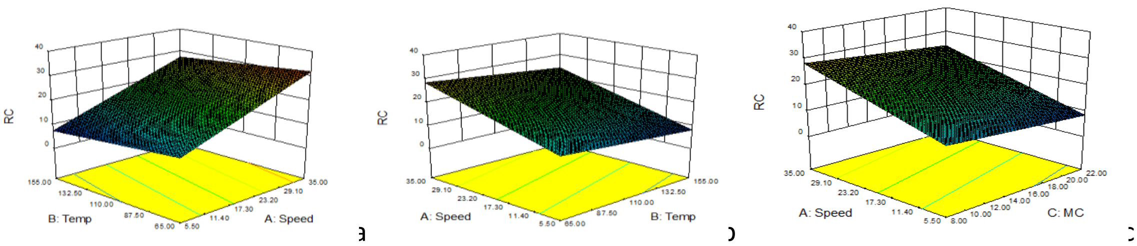


Fig.3. Response surface contours for RC. For each contour plots, the third variable is fixed.

Effects of speed, temperature and moisture content on RE

There was a very strong and significant influence of the quadratic factors of conveyor speed, moisture content of maize and temperature on roasting efficiency (Table 4). Statistical analysis conducted on the data showed that the model was significant ($p \leq 0.05$), equation 6. Conveyor speed, moisture content of maize and temperature were significant ($p \leq 0.05$) with quadratic effects on the model. The model could explain 83.35% of the variations in roasting efficiency, meaning only 16.65% of the variation were due to other factors not included in the model. The response plots (Figure 4a–c) show that speed, moisture content and temperature, all had significant effects on the roasting efficiency of the roaster with significant interaction between all the factors. The response surface plots generated showed curvilinear plots with conveyor speed and linear plots with both temperature and moisture content of maize (Figure 4a–c). This implies that the roasting efficiency of the roaster increased as speed and temperature increased. A similar model was obtained whenART/98/SW06-OB-W was used to evaluated the roaster [28] but, R^2 obtained in this study was about 4% higher.

$$RE = 77.17752 - 2.16603S + 0.40062T - 2.47911Mc - 5.12386\text{E-}003ST + 4.70548\text{E-}003SMc + 8.25772\text{E-}003TMc + 0.068967S^2 - 6.75346\text{E-}004T^2 + 2.98488\text{E-}003Mc^2 \; (R^2 = 0.8335). \tag{6}$$

Table 4. ANOVA for quadratic model of RE

Source	Sum of Squares	Df	Mean Square	F Value	p-value Prob > F	
Model	9370.37	9	1041.15	19.47	< 0.0001	significant
A-Speed	3.59	1	3.59	0.067	0.7970	
B-Temp	1190.03	1	1190.03	22.25	< 0.0001	
C-MC	579.07	1	579.07	10.83	0.0023	
AB	35.48	1	35.48	0.66	0.4208	
AC	0.54	1	0.54	0.010	0.9204	
BC	154.77	1	154.77	2.89	0.0978	
A^2	192.28	1	192.28	3.60	0.0662	
B^2	170.99	1	170.99	3.20	0.0824	
C^2	0.062	1	0.062	1.151E-003	0.9731	
Residual	1871.58	35	53.47			
Cor Total	11241.95	44				

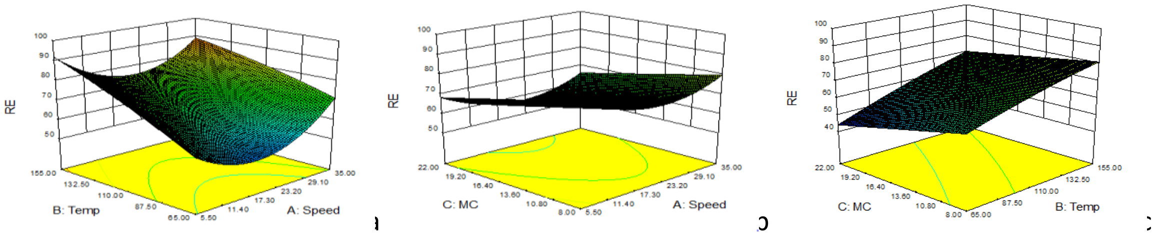


Fig.4. Response surface contours for RE. For each contour plots, the third variable is fixed.

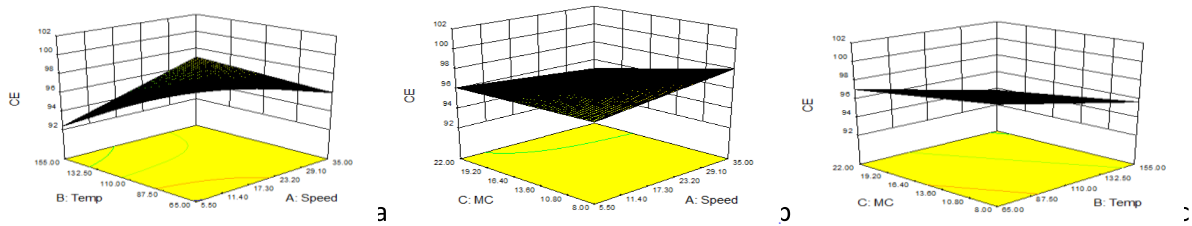
Effects of speed, temperature and moisture content on CE

The results of regression analysis show that all the factors did affect conveyance efficiency CE ($p < 0.05$), the analysis of variance reveals that regression was statistically significant at 60.33% confidence level (Table 5), equation 7, and the high coefficient of determination ($R^2 = 60.33$) demonstrates that the model could be used to explain 60.33% of the total variation in the response. As Figure 5a-c show, conveyance efficiency CE optimization required simultaneous decrease in speed and temperature. The best CEvalues were attained working at low speed and low temperature, conditions under which a slight reduction in the parameters will yield a corresponding increase in the conveyance efficiency.

$$CE = 106.81499 - 0.18771S - 0.10311T + 0.064372Mc + 3.31337\text{E-}003ST - 0.011181SMc - 1.25483\text{E-}004TMc \quad (R^2 = 0.6033). \qquad (7)$$

Table 5. ANOVA for 2FI model of CE

Source	Sum of Squares	Df	Mean Square	F Value	p-value Prob > F	
Model	255.97	6	42.66	9.63	< 0.0001	significant
A-Speed	0.084	1	0.084	0.019	0.8912	
B-Temp	164.54	1	164.54	37.14	< 0.0001	
C-MC	9.61	1	9.61	2.17	0.1490	
AB	79.99	1	79.99	18.06	0.0001	
AC	3.06	1	3.06	0.69	0.4112	
BC	0.036	1	0.036	8.068E-003	0.9289	
Residual	168.33	38	4.43			
Cor Total	424.29	44				



Effects of speed, temperature and moisture content on MD

There was a significant ($p \leq 0.05$) influence of the linear factors of conveyor speed and temperature on the mechanical damage (Table 6), equation 8. It was observed from the statistical analysis that both conveyor speed and temperature had significant ($p \leq 0.05$) linear effect on the model. The model could explain about 89.25% of the variations in mechanical damage. As shown in the response plots (Figure 6a–c), both speed, and moisture content had significant effects on the mechanical damage of the Suwan-1-SR-Y maize. Therefore, mechanical damage of the roaster increased as speed and temperature increased.

$$MD = 0.027613T + 0.020238Mc - 0.0337S - 1.87475 \quad (R^2\ 0.8925). \qquad (8)$$

Table 6. ANOVA for linear model of MD

Source	**Sum of Squares**	**Df**	**Mean Square**	**F Value**	**p-value Prob > F**	
Model	177.34	3	59.11	113.49	< 0.0001	significant
A-Speed	1.49	1	1.49	2.86	0.0981	

B-Temp	92.94	1	92.94	178.44	< 0.0001	
C-MC	0.34	1	0.34	0.66	0.4216	
Residual	21.36	41	0.52			
Cor Total	198.70	44				

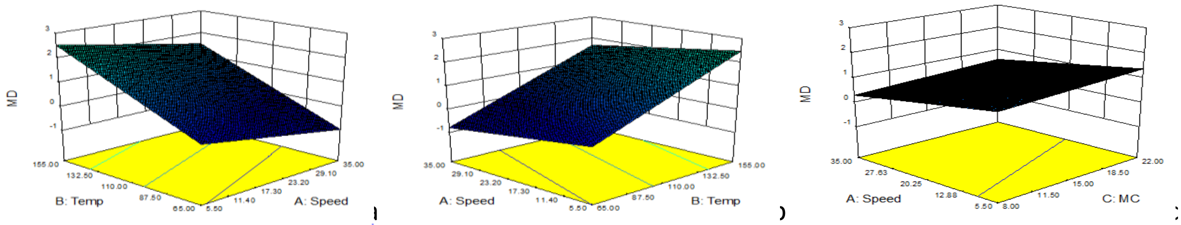


Fig.6. Response surface contours for MD. For each contour plots, the third variable is fixed.

IV. CONCLUSION

From the results obtained in this study, the following conclusions were drawn; the roasting efficiency increase with increases in speed of auger and set temperature. The roasting efficiency, conveyance efficiency and mechanical damage observed from the performance evaluation have very high correlation (0.8335, 0.6033 and 0.8925) with the factors. The predicted roasting equations showed that all the variation in factors of speed, temperature and moisture content contributed to the total variation in the roaster performance (R^2 = 0.3409 to 0.8925).

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A. O. Atere, et. al. "Modelling the Performance of a Roasting Machine." *American Journal of Engineering Research (AJER)*, vol. 9(8), 2020, pp. 75-82.