A Mathematical Model for Predicting the Winnowing Efficiency of Bambara Groundnut Sheller

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Abstract—A mathematical model for predicting the winnowing efficiency of bambara groundnut sheller was developed. The regression equation for model simulation was developed using Least Square Method. The model was verified and validated by fitting it into established experimental data from winnowing efficiency of already existed Bambara groundnut sheller. The result revealed that the fitted model correlated well with the experimental data with R-square value of 0.99. The winnowing efficiency obtained from the predicted model was approximately the same values with the experimental values. Therefore, the model equation was considered to be reasonably good for predicting the winnowing efficiency of bambara groundnut sheller for known values of moisture content and blower speed.

Index Terms—Bambara Groundnut Sheller, Blower Speed, Modeling, Moisture Content.

I. INTRODUCTION

One of the major significances of modeling a physical system is to have an explicit and detailed understanding of the fundamental mechanisms of that system and also guide in establishing optimum conditions for the construction and operation of that system, thereby resulting in an improved efficiency. According to Anu [4], a model is similar to but simpler than the system it represents. A good model is a judicious tradeoff between realism and simplicity. Optimum conditions are those that produce the most favorable or most beneficial result from a system. A model would have greater confidence if a good and a high significance level is attained [13].

Bambara groundnut (**Vigna subterranea***) is one of the underutilized food crops but has gained a renewed interest and received more attention in the recent years. Bambara groundnut (**Vigna subterranea***) belongs to the family of fabaceae (Fig. 1). It is an annual herbaceous, intermediate plant with creeping stems. In Nigeria, it is known as Gurjiya or Kwaruru in Hausa, Okpa in Igbo, Epa-Roro in Yoruba [10]. The colour of the seeds differ from white, cream, red, black and in some cases mottled with colours such as brown, red or black [10].

The seeds (ripe or immature) of Bambara groundnut (**Vigna subterranea***) contains about 20% protein, 60% carbohydrates and 7% oil (Fig. 2). Lysine and Leucine are the predominant essential amino acids found in bambara groundnut [7].

It is used for both human and animal consumption. The crop is popular in Africa because of its resistance to drought and pests, and its ability to produce reasonable yields when grown on poor soils. The crop ranks third among the grain legume crops of Africa in terms of production and consumption after groundnut and cowpea and it is consumed in many ways. It can either be eaten in its young stage or when it is ripe [9].

Separation of materials other than grains is essential to upgrade the quality of food material. Some of the methods employed for separating materials other than grains include winnowing, aspiration, sieving and use of vertical airstream [1].

According to Baryeh [9], the optimum performance of the Bambara nut cracker may be attained within a certain range, therefore modeling enables the incorporation of all the necessary parameters/features of the physical system and allows quick and easy evaluation of different performance alternative leading to optimal solution. To this end, the objectives of this study is to determine the parameters that would give the optimum winnowing efficiency of Bambara groundnut sheller, obtain the parameters with the required moisture content for optimum separation and evaluate the

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parameters by comparing the experimental studies in order to predict or recommend the moisture content and blower speed required to separate the shell from seeds of bambara nuts.

II. MODEL CONCEPTUALIZATION

A. Purpose of the Model

The speed of the impeller arm, moisture content, seed density etc have significant effect on the cracking efficiency of the Bambara groundnut sheller while the duct cross-sectional area, terminal velocity of the seed and blower speed etc have significant effect on the separating efficiency of the Bambara groundnut sheller [3].

B. The Model Boundary

The model parameters considered for the system (Bambara groundnut sheller) are; Moisture content and Blower speed.

C. Reference Model

Literature revealed that moisture content and drying temperature affects the toughness and rupture force of the nut. These presented data on the effects which could be used in determining the energy requirements on cracking of the nuts to extract the seeds. The study of Adigun and Oje [2] revealed that orientation of nuts affects its cracking and winnowing.

D. Nature of the Basic Mechanism

The basic mechanism represents the smallest set of realistic cause-and-effect relations capable of generating the reference mode. The basic mechanisms may also be thought of as the simplest story that explains the dynamic behaviour of the system.

III. MATERIALS AND METHODS

A. Moisture Content Determination

The moisture content of the pods was varied to have five moisture levels using the method of Aviara et al. [8] and Oluwole et al. [17]. This method involved the soaking of a bulk quantity of the pods in ordinary water 60, 90, 120, 150 and 180 minutes, respectively. At the end of each period of soaking, the pods were spread out in a thin layer to dry in natural air for about eight hours. The pods were then sealed in marked polyethylene bags and stored in the same condition for a further 24 hours. This enables stable and uniform moisture content of the pods to be achieved in the bags.

The moisture content of each sample was determined using the method described by ASABE [6] and Oje [16]. The method involved oven drying of pod samples at 105°C with weight loss moisture on hourly basis to give an ideal of the time at which the weight began to remain constant. After oven drying for 6 hours, the pods were weighed using an electric weighing balance to 0.001g to determine the final weight. The moisture content was determined using the formula in Equation (1) as given by Oluwole et al. [17].

\[ M_C = \left[ \frac{(W_i - W_f)}{W_i} \right] \times 100\% \text{ (d.b)} \]  

where,  \( M_C = \) Moisture content, \%  
\( W_i = \) Initial mass of pods, g  
\( W_f = \) Final mass of pods, g  
\( \text{d.b} = \) dry basis

B. Model Formulation

1) Model Development

The regression equation for model simulation is developed using Least Square Method.

The regression model equation for the predicted values of the Winnowing Efficiency is given in Equation (2) as:

\[ Y = \beta_0 + \beta_1X_1 + \beta_2X_2 \]  

where \( \beta_0 = \) mean value  
\( \beta_0 = [X'] \beta_2 = [X']Y' = \) regression coefficients  
\( X_1 = MC = \) Moisture Content (% db)  
\( X_2 = SP = \) Winnowing Speed (rpm)

Evaluating the regression coefficients \( \beta_0, \beta_1, \) and \( \beta_2 \) using matrix coding, as presented in Table I.

\[ [X] = 15 \times 3 \text{ Matrix} \]  
\[ [Y] = 15 \times 1 \text{ Matrix} \]  
\[ [X']} = \begin{bmatrix} 15 & 196.8 & 21250 \\ 196.8 & 3079.38 & 278800 \\ 21250 & 278800 & 31712500 \end{bmatrix} \]  
\[ [X']Y' = \begin{bmatrix} 798.8 \\ 8729.7 \\ 1158450 \end{bmatrix} \]  
\[ [X']^{-1} = \begin{bmatrix} 1.673 & -0.0266 & -0.000877 \\ -0.0266 & 0.00203 & 0 \\ -0.000877 & 0 & 0.00000626 \end{bmatrix} \]  
\[ [X']^{-1} \times [X']Y' = \begin{bmatrix} 1.673 & -0.0266 & -0.000877 \\ -0.0266 & 0.00203 & 0 \\ -0.000877 & 0 & 0.00000626 \end{bmatrix} \times \begin{bmatrix} 798.8 \\ 8729.7 \\ 1158450 \end{bmatrix} \]  
\[ = \begin{bmatrix} 75.8 \\ -3.51 \\ 0.0171 \end{bmatrix} \]

Therefore, the model developed from the experimental result is given in Equation (4) as:

\[ Y = 75.8 - 3.51MC + 0.0171SP \]

where, \( MC = \) Moisture Content (% d.b)  
\( SP = \) Blower or Winnowing Speed (rpm).

The model equation is for the winnowing efficiency and it can be simulated to obtain an optimum efficiency at a
specific range of moisture content and winnowing speed combination. Table I gives a brief illustration of the performance parameters relating moisture content and blower speed with winnowing efficiency as the response.

TABLE I: PERFORMANCE PARAMETERS FOR THE BAMBARA GROUNDNUT SHELLER [18]

| S/N | Code | MC (% d.b) | SP (rpm) | Response (%) |
|-----|------|------------|----------|--------------|
| 1   | 1    | 5.2        | 1800     | 86.7         |
| 2   | 1    | 8.9        | 1800     | 75.2         |
| 3   | 1    | 12.9       | 1800     | 57.6         |
| 4   | 1    | 17.2       | 1800     | 46.9         |
| 5   | 1    | 21.4       | 1800     | 32.7         |
| 6   | 1    | 5.2        | 1450     | 82.5         |
| 7   | 1    | 8.9        | 1450     | 70.0         |
| 8   | 1    | 12.9       | 1450     | 53.3         |
| 9   | 1    | 17.2       | 1450     | 37.4         |
| 10  | 1    | 21.4       | 1450     | 25.4         |
| 11  | 1    | 5.2        | 1000     | 75.4         |
| 12  | 1    | 8.9        | 1000     | 60.0         |
| 13  | 1    | 12.9       | 1000     | 47.4         |
| 14  | 1    | 17.2       | 1000     | 28.7         |
| 15  | 1    | 21.4       | 1000     | 18.6         |

2) Formulation of Optimization Function

The method used in the optimization is based on the procedure presented by Ndrikika [14]; Muna et al. [15] which has the following two characteristics:

i. An objective function stating the quality to be minimized or maximized and its functional dependence from design variables, and

ii. Constraints on the design variables under which an optimum is to be searched, expressed mathematically as presented in Equations (5) and (6).

Optimize \( V_0 = G_0 (X_1, X_2 \ldots \ldots, X_n) \)  

Subject for \( a_0 < X_1 < b_1 \) and \( a = 1, 2, 3, \ldots, n \)

where \( V_0 = \) objective function

\( G_0 \) = some relationship between \( V_0 \) and \( X \)

\( X_1 \) = Design variables

\( a_0 b_1 \) = lower and upper boundary respectively.

For this study, the objective function considered was to obtain the optimum winnowing efficiency. The design variables used in the optimization are moisture content, \( (MC) \) and blower speed \( (SP) \). The lower and upper limits of the design variables which are incorporated as constraints for the different moisture levels are as follows:

i. \( 5.2 \leq MC \leq 21.4 \) g [18].

ii. \( 1000 \leq \text{rpm} \leq 1800 \text{ rpm} \) [18].

IV. RESULTS AND DISCUSSION

A. Model Verification and Validation

Model validation techniques include simulating the model under known input conditions and comparing model output with system output [4].

Model verification and validation were done by carrying out the following statistical computations and analysis using Microsoft Excel:

i. Regression analysis to compute the coefficient of determination \( (R^2) \) and coefficient of correlation \( (r) \) [12].

ii. Plot of scattered diagram of predicted and experimental values; and determine the degree to which the predicted and experimental values are related [19].

iii. Analysis based on reduced Chi-square \( (\chi^2) \), mean bias error \( (MBE) \) and root mean square error \( (RMSE) \) [11,5].

These values are obtained with reference to Equations (7) to (9) as:

(a) Reduced Chi-square \( (\chi^2) \)

\[ \chi^2 = \sum_{i=1}^{N} (\text{MR}_{\text{exp}} - \text{MR}_{\text{pre}})^2/N - Z \]  

(b) Mean bias error \( (MBE) \)

\[ MBE = \frac{1}{N} \sum_{i=1}^{N} (\text{MR}_{\text{exp}} - \text{MR}_{\text{pre}}) \]

(c) Root mean square error \( (RMSE) \)

\[ RMSE = [\frac{1}{N} \sum_{i=1}^{N} (\text{MR}_{\text{exp}} - \text{MR}_{\text{pre}})^2]^{1/2} \]

where \( \text{MR}_{\text{exp}} \) = experimental values,

\( \text{MR}_{\text{pre}} \) = predicted values,

\( N \) = number of observations,

\( Z \) = number of constants and

\( \chi^2 \) = Chi-square.

For a perfect goodness of fit, the value of \( R^2 \) should be equal to \( r \) (that is, \( R^2 = r = 1 \)) and also greater than the values of \( \chi^2 \); MBE and RMSE [11,5].

The experimental and predicted values of winnowing efficiency at five levels of moisture content (5.2 - 21.4 % d.b) and three levels of blower speed (1000 - 1800 rpm) is presented in Table II.

TABLE II: EXPERIMENTAL AND PREDICTED VALUES OF WINNOWING EFFICIENCY

| MC (% d.b) | SP (rpm) | Experimental Values (%) | Predicted Values (%) |
|------------|----------|-------------------------|---------------------|
| 5.2        | 1800     | 86.7                    | 88.3                |
| 8.9        | 1800     | 75.2                    | 75.3                |
| 12.9       | 1800     | 57.6                    | 61.3                |
| 17.2       | 1800     | 46.9                    | 46.2                |
| 21.4       | 1800     | 32.7                    | 31.5                |
| 5.2        | 1450     | 82.5                    | 82.3                |
| 8.9        | 1450     | 70                      | 69.4                |
| 12.9       | 1450     | 53.3                    | 55.3                |
| 17.2       | 1450     | 37.4                    | 40.2                |
| 21.4       | 1450     | 25.4                    | 25.5                |
| 5.2        | 1000     | 75.4                    | 74.6                |
| 8.9        | 1000     | 60                      | 61.7                |
| 12.9       | 1000     | 47.4                    | 47.6                |
| 17.2       | 1000     | 28.7                    | 32.5                |
| 21.4       | 1000     | 18.6                    | 17.8                |

From Table II, the values of moisture content (MC) and its corresponding blower speed (SP) were fitted into the
model equation to obtain the predicted values of winnowing efficiency. Comparing the experimental values with the predicted values, it was revealed that model had the capacity of predicting values for optimum winnowing efficiency for bambara groundnut sheller.

Line of good fit was presented graphically (Fig. 3) and also used to compare the predicted values with the experimented values. Thus, the plot in Fig. 3 indicated that the points for experimental and predicted values have positive correlation. This implies that there is an excellent agreement between the predicted values and the experimented values.

The values of coefficient of determination ($R^2 = 0.9989$) and correlation ($r = 0.9994$) are approximately equals to 1 (Table III). The goodness of fit was further evaluated based on the values of root mean square error (RMSE), mean bias error (MBE) and reduced Chi-square ($\chi^2$). The values of $R^2$ of the model equation was higher than the values of $\chi^2$. MBE and RMSE. These are characteristic of good quality fit. Therefore, the model equation is considered to be reasonably good for predicting winnowing efficiency if the moisture content and blower speed are known.

**TABLE III: STATISTICAL PARAMETERS FOR GOODNESS OF FIT FOR MODEL EQUATION**

| Parameters                          | Values    |
|------------------------------------|-----------|
| Coefficient of correlation, $r$    | 0.9994    |
| Coefficient of determination, $R^2$ | 0.9989    |
| Reduced Chi-square, $\chi^2$       | -0.0866   |
| Mean bias error, MBE               | -0.0333   |
| Root mean square error, RMSE       | 0.8240    |

**V. CONCLUSION**

Based on the excellent correlation between the experimental and predicted values, it was therefore concluded that the model equation developed was found to be reasonably good for predicting the optimum winnowing efficiency for bambara groundnut sheller.

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