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# Modelling the Kinetics of Thin Layer Drying of Cocoa Beans in a Passive Solar Dryer under Nsukka Climatic Condition

**By**

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***Abstract***
*Drying experiments were conducted on cocoa beans using a mixed mode passive solar dryer and open sun drying methods. The drying data obtained from the experiments were fitted into ten different published thin layer drying models. The performance of these models was examined by comparing the coefficient of correlation ($R^2$), reduced Chi-square ($\chi^2$) and root mean square error (RMSE) between the experimental and predicted values of moisture ratios. Among these models, the Midili-Kucuk model showed good agreement with the data obtained from the experiments for both the solar drying and the open-air sun drying method under the conditions tested.*

***Keywords:*** *Cocoa beans, Modelling, Solar drying, Sun drying, Moisture ratios.*

## 1. Introduction

Cocoa beans the world over has remained relevant for a variety of uses and Nigeria has her own fair share in contributing to the world market. Since the introduction of the crop (cocoa) into Nigeria in about 1874 [1], fourteen (14) of Nigeria's 36 states grow cocoa: Abia, Adamawa, Akwa-Ibom, Cross-River, Delta, Edo, Ekiti, Kogi, Kwara, Ogun, Ondo, Osun, Oyo, and Taraba [2, 3]. Out of these states, the South Western States of Nigeria, which include: Ondo, Oyo, Osun, and Ekiti are regarded as the "cocoa belt" of Nigeria, out of which Ondo is regarded as the highest producing state [4]. The cocoa beans produced in Nigeria, Africa, as well as other countries of the world are basically for its chocolate which has alternative uses, and applications.

Cocoa beans is mainly consumed as chocolates and widely used in beverages, cosmetics, pharmaceuticals and toiletry products [5, 6]. It is also associated with health benefits such as anti-carcinogenic, anti-athergenic, anti-ulcer, anti-thrombotic, anti-inflammatory, immune modulating, anti-microbial, vasodilatory, and analgesic [7, 8]. Other uses include the use of the shells for stock feed and manure. It is also a source of theobromine, shell fat and vitamin D. The pod of cocoa is rich in potash, and it is used for soap production which is a product obtained from the primary processing of cocoa beans.

Upon harvesting of ripe cocoa pods, fresh cocoa beans are fermented in wooden boxes for 5-7 days and dried until it reaches the safe moisture level of between 6 and 8 % (wet basis). Drying techniques vary among the farmers and it ranges from the natural sun drying technique to the artificial hot air technique. The selection of drying technique largely depends on the production scale and affordability in terms of cost. Currently, sun drying is still the most widely used method especially by cocoa smallholders due to its simplicity, low cost set up and requires only direct sunlight which is renewable and abundant. It was also reported that sun dried cocoa beans have better flavour quality and less acidic due to its gentle drying process [9]. On the other hand, artificial hot air drying method is normally associated with beans of weaker flavour quality, higher acidity, insufficient browning, smoke contamination and case hardening [10]. Mathematical modelling of the cocoa drying process has been reported in literatures mostly in hot air drying under continuous operation [11 – 14]. However, there is no report at all on modelling of the thin layer drying kinetics of cocoa beans using a mixed mode passive solar dryer and the open sun drying methods. New semi-theoretical models were also proposed to better suit the drying kinetics. Therefore, the present study was carried out to model the thin layer drying kinetics of cocoa beans in a passive solar dryer and under open sun and to select the best model for these processes.

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## 2. Materials and Methods

### 2.1 Sample preparation

Fresh cocoa beans were obtained from a cocoa farm in Ikom, Cross River State Nigeria after fermentation using wooden boxes for five days. After the fermentation process, the beans were dried using both the solar drying and the open sun drying methods for two days in Nsukka, Enugu State, Nigeria.

### 2.2 Drying procedure

Drying commenced from 12 noon till 6 p.m. on the first day, and 10 a.m. till 6 p.m. the following day. The drying was terminated by 6 p.m. the second day when the beans moisture content reached 7.5 % (wet basis) for the solar dried sample and 7.33 % (wet basis) for the open sun dried sample. These values fall within the range of the safe moisture contents of cocoa of between 6 and 8 % moisture content wet basis. Moisture contents of the beans in both methods were taken every 2 hours using a weighing balance, after the taking the initial moisture content using the digital OHAUS moisture analyzer.

### 2.3 Temperature and relative humidity measurements

The temperature and relative humidity measurements for both the solar drying chamber and ambient (open sun) were taken using a clinical thermometer and a digital hygrometer respectively.

## 3. Mathematical modelling

The ten (10) thin layer drying models listed in Table 1 were used. These are semi-theoretical and empirical models used in literatures. Semi-theoretical models are derived based on theoretical model (Fick's second law) but are simplified and added with empirical coefficients in some cases to improve curve fittings. In the empirical models a direct relationship is derived between moisture content and added with empirical coefficients in some cases to improve curve fitting. In the empirical models, a direct relationship is derived between moisture content and drying time and the parameters associated with it have no physical meaning at all.

In these models, the moisture ratio (MR) is defined as $(M_i - M_e)/(M_o - M_e)$ where the subscripts i, e and o denote at time i, equilibrium and initial, respectively. Non-linear regression was performed using the least square method with a aid of a nonlinear regression software for the generation of the constants called NLREG (version 6.3). Statistical parameters such as the coefficient of determination ($R^2$) (Equation 11a or 11b), reduced chi-square (Equation 12) and root mean square error (Equation 13) were used as the criteria for selecting the best model.

**Table 1: Thin layer drying models tested for cocoa drying**

| Model name | Model equation | Equation no. | References |
|---|---|---|---|
| Newton | $MR = \exp(-kt)$ | 1 | [15] |
| Henderson and Pabis | $MR = a\exp(-kt)$ | 2 | [16] |
| Page | $MR = \exp(-kt^n)$ | 3 | [17] |
| Logarithmic | $MR = a\exp(-kt) + c$ | 4 | [18] |
| Two term model | $MR = a\exp(-kt) + c\exp(-gt)$ | 5 | [19] |
| Verma *et al.* | $MR = a\exp(-kt) + (1 - a)\exp(-gt)$ | 6 | [20] |
| Diffusion approach | $MR = a\exp(-kt) + (1 - a)\exp(-kgt)$ | 7 | [16] |
| Midili-Kucuk | $MR = a\exp(-kt^n) + bt$ | 8 | [21] |
| Wang and Smith | $MR = 1 + at + bt^2$ | 9 | [22] |
| Hi *et al.* | $MR = a\exp(-kt^n) + c\exp(-gt^n)$ | 10 | [23] |

### 3.1 Coefficient of determination ($R^2$)

The Coefficient of determination or correlation coefficient, $R^2$ can be used to test the linear relation between measured and estimated values, which can be calculated from the equation given below:

$$R^2 = 1 - \left[\frac{\sum_{i=1}^{N}(MR_{pre,i} - MR_{exp,i})^2}{\sum_{i=1}^{N}(MR_{pre,i} - \overline{MR}_{exp,i})^2}\right] \quad (11a)$$

or simply put:

$$R^2 = \frac{N\sum_{i=1}^{N} MR_{pred,i}MR_{exp,i} - \sum_{i=1}^{N} MR_{expt\,x,i}}{\sqrt{\left[N\sum_{i=1}^{N} MR_{pred,i}^2 - \left(\sum_{i=1}^{N} MR_{pred,i}\right)^2\right]\left[N\sum_{i=1}^{N} MR_{expt,i}^2 - \left(\sum_{i=1}^{N} MR_{expt,i}\right)^2\right]}} \quad (11b)$$

where $R^2$ is called the coefficient of determination, $MR_i$ is the i^th moisture ratio, $MR_{exp,i}$ stands for the experimental moisture ratio found in any measurement, $MR_{pre,i}$ is the moisture ratio for this measurement and N is the total number of observations.

### 3.2 Reduced Chi-Square ($\chi^2$)

Reduced Chi-square test (or Pearson's Chi-square test), also known as the chi-square goodness-of-fit test or chi-square test for independence, is one of the statistical measures for goodness-of-fit in a regression model. The formula for Reduced Chi-square is expressed as:

$$\chi^2 = \frac{\sum_{i=1}^{N}(MR_{expt,i} - MR_{pred,i})^2}{N - z} \quad (12)$$

where $MR_{expt,i}$ and $MR_{pred,i}$ are the experimental and predicted dimensionless moisture ratios, $MR$ respectively, N is the number of observations, and z is the number of constants.

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### 3.3 Root Mean Squared Error (RMSE)

This is the root of the mean/average of the square of all the errors. The use of RMSE is very common and it makes an excellent general purpose error metric for numerical predictions. The root mean square error (RMSE) has been used as a standard statistical metric to measure model performance in various fields of studies including engineering, meteorology, air quality, and climate research studies [24]. The formula for Coefficient of determination in expressed as:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(MR_{expt,i} - MR_{pred,i})^2} \quad (13)$$

It provides information on the short term performance. The value of RMSE is always positive, represented as zero in the ideal case, therefore, the smaller the value of the RMSE, the better the model. It is a measure of squared deviations. The error occurs because of randomness.

## 4. Results and Discussion

### 4.1 Mathematical modelling of solar and open sun drying curves

In order to fit the drying curves, the moisture content data of cocoa bean in both the drying chamber of the solar dryer and under open sun, obtained experimentally was converted to the dimensionless moisture ratio. The curve fitting calculations with drying time were carried out on the ten thin layer drying models given by previous researchers presented in Table 1. The non-linear regression analysis was carried out using NLREG software (version 6.3) to obtain the values of drying constants and coefficients of these thin layer drying models.

Tables 2 and 3 show the results of the regression analyses performed on the experimental data. In all cases (from Tables 2 and 3), the statistical parameters estimations showed that $R^2$, $\chi^2$, and RMSE values ranged from 0.9420 to 0.9892, 0.000677 to 0.003499, and 0.018587 to 0.050751, respectively.

The model that best described the thin layer drying characteristics (that is, the model that gives the best fit to the drying curves) is the one that gives the highest $R^2$ and lowest $\chi^2$ and RMSE values. Based on these criteria, the *Midili-Kucuk model* was found to be the best (hence, the accepted) model that described both drying curves (that is, solar and open sun) with $R^2$, $\chi^2$, and RMSE values of 0.9892, 0.000677, 0.018587 for the solar drying method and 0.9771, 0.001293, 0.028259 for the open sun drying method respectively. The second best fitted models were found to be the logarithmic model with $R^2$, $\chi^2$, and RMSE values of 0.9867, 0.000691, 0.020567, and 0.9768, 0.001597, 0.028430 for both the solar drying and open sun drying methods respectively. While the Hi *et al.* model was the third best fitted model with $R^2$, $\chi^2$, and RMSE values of 0.9830, 0.001430, 0.023155, and 0.9720, 0.002567, 0.031024 for both the solar drying and open sun drying methods respectively.

**Table 2:** The values of model constants and statistical parameters during drying of cocoa beans in a solar dryer

| S/No. | Model name | Model constants | $R^2$ | $\chi^2$ | $RMSE$ |
|---|---|---|---|---|---|
| 1 | Newton | $k = 0.095888$ | 0.9647 | 0.001610 | 0.037532 |
| 2 | Henderson and Pabis | $a = 0.911732$, $k = 0.084595$ | 0.9759 | 0.000983 | 0.027155 |
| 3 | Page | $k = 0.128865$, $n = 0.86742$ | 0.9698 | 0.001290 | 0.031108 |
| 4 | Logarithmic | $a = 1.574812$, $k = 0.03301$, $c = -0.726051$ | 0.9867 | 0.000677 | 0.020567 |
| 5 | Two term model | $g = 0.142995$ | 0.9825 | 0.001093 | 0.023375 |
| 6 | Verma *et al.* | $a = 0.088268$, $k = 10.461133$, $g = 0.084595$ | 0.9759 | 0.001180 | 0.027155 |
| 7 | Diffusion approach | $a = 1$, $k = 0.095888$, $g = 1$ | 0.9647 | 0.002254 | 0.037532 |
| 8 | Midili-Kucuk | $a = 220.855579$, $k = 5.534609$, | 0.9892 | 0.000691 | 0.018587 |

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| | | | | | |
|---|---|---|---|---|---|
| | | $n = 0.017117$, $b = -0.029058$ | | | |
| 9 | Wang and Smith | $a = -0.086381$, $b = 0.002401$ | 0.9518 | 0.002644 | 0.044527 |
| 10 | Hi *et al.* | $a = 0.407765$, $k = 0.031977$, $n = 1.343945$, $c = 0.401756$, $g = 0.031977$ | 0.9830 | 0.001430 | 0.023155 |

**Table 3:** The values of model constants and statistical parameters during drying of cocoa beans in the open sun

| S/No. | Model name | Model constants | $R^2$ | $\chi^2$ | $RMSE$ |
|---|---|---|---|---|---|
| 1 | Newton | $\mathrm{k} = 0.093390$ | 0.9452 | 0.002460 | 0.046393 |
| 2 | Henderson and Pabis | $a = 0.932594$, $k = 0.084993$ | 0.9455 | 0.002333 | 0.041829 |
| 3 | Page | $k = 0.110210$, $n = 0.926283$ | 0.9420 | 0.002702 | 0.045016 |
| 4 | Logarithmic | $a = 26.541103$, $k = 0.001556$, $c = -25.70695$ | 0.9768 | 0.001293 | 0.028430 |
| 5 | Two term model | $a = 0.460392$, $k = 0.084993$, $c = 0.472202$, $g = 0.084993$ | 0.9455 | 0.003499 | 0.041829 |
| 6 | Verma *et al.* | $a = 0.932594$, $k = 0.084993$, $g = 12.524707$ | 0.9455 | 0.002799 | 0.041829 |
| 7 | Diffusion approach | $a = 1$; $k = 0.093390$, $g = 1$ | 0.9452 | 0.003444 | 0.046393 |
| 8 | Midili-Kucuk | $a = 21.583296$, $k = 3.239309$, $n = 0.006375$, $b = -0.038380$ | 0.9771 | 0.001597 | 0.028259 |
| 9 | Wang and Smith | $a = -0.080092$, $b = 0.001934$ | 0.9420 | 0.003434 | 0.050751 |
| 10 | Hi *et al.* | $a = 0.414344$, $k = 0.012026$; $n = 1.707588$, $c = 0.356421$, $g = 0.012026$ | 0.9720 | 0.002567 | 0.031024 |

### 4.2 Validation of the Accepted Models

Validation of the accepted model was carried by plotting the experimental moisture ratio values with the predicted moisture ratio values. The performance of the model for both the solar dryer and open sun drying methods is illustrated in Figures 1 and 2 respectively. It can be seen that, the accepted

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model (Midili-Kucuk) was in good agreement with the experimental results. The established model, therefore, gave an excellent fit to drying curves.

Figures 1 and 2 show that the experimental data generally band around the straight line representing predicted data in each case, which demonstrates the appropriateness of Midili-Kucuk mathematical model in describing the drying behaviour of cocoa beans. Hence, their $R^2$ values of 0.9892 and 0.9771 for the solar drying and open sun drying methods indicate that 98% and 97% of their drying behaviours were predicted by this model. This validates that Midili-Kucuk model could be used to explain thin layer solar or sun drying behaviour of cocoa beans.

The accepted and validated Midilli *et al.* model as the best model among the selected ten (10) models tested using the experimental data from the drying experiment (using cocoa beans for the present study) was developed in the year 2002 by the researchers (Midilli, A., and Kucuk, H) for single or thin layer drying of agricultural produce. This model has been validated and could be used for predicting the moisture ratio values and drying time of green peas [25] (Sunil *et al.*, 2013) and now for cocoa beans in the present study.

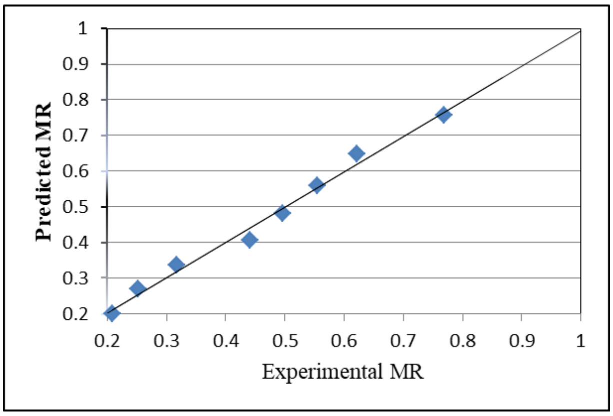


**Figure 1:** Comparison of experimental moisture ratio with predicted moisture ratio for solar drying using the Midili-Kucuk model ($R^2, \chi^2$ and RMSE values of 0.9892, 0.000677 and 0.018587 respectively)

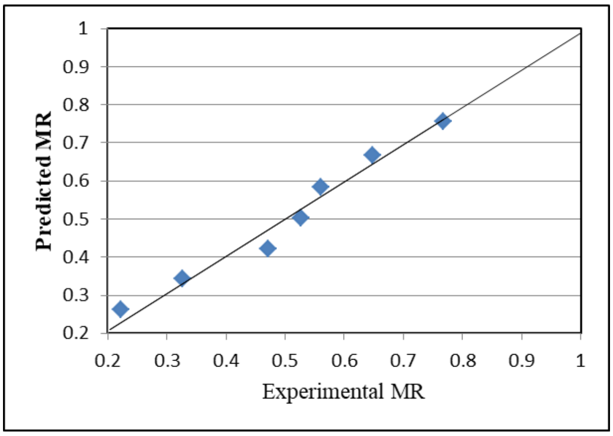


**Figure 2:** Comparison of experimental moisture ratio with predicted moisture ratio for open sun drying using the Midili-Kucuk model ($R^2, \chi^2$ and RMSE values of 0.9771, 0.001293 and 0.028259 respectively)

## 5. Conclusions

Regression analyses were carried out to select the thin layer model that best described the drying kinetics of the solar dried and open sun dried samples of cocoa beans. Of all the ten (10) thin layer drying models that were fitted to the experimental data obtained from drying the cocoa bean samples, the Midili-Kucuk model gave an excellent fit to the experimental data and was found to be the best (hence, the accepted and validated) model that described both drying curves (that is, the solar dried and open-air sun dried samples) with $R^2$, $\chi^2$, and RMSE values of 0.9892, 0.000677, 0.018587 for the solar drying method and 0.9771, 0.001293, 0.028259 for the open-air sun drying (control) method respectively. Thus, Midili-Kucuk model could be used to predict the *moisture ratio values and drying time* of cocoa beans.

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