American Journal of Food Science and Technology, 2017, Vol. 5, No. 3, 93-100
Available online at http://pubs.sciepub.com/ajfst/5/3/4

DOI:10.12691/ajfst-5-3-4

Selection and Verification of a Drying Model for Maize (*Zea mays L.*) in Forced Convection Solar Grain Dryer

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Abstract Various researchers have fitted experimental drying curves for various products to existing drying models. In this study, an experimental forced convection solar grain dryer was used to select the best fitting drying model for shelled maize. 0.04 m thick grain layer of shelled maize was dried an air velocity of 0.408 m/s and a 40°C drying air temperature. Using Root Mean Square Error (RMSE), Coefficient of Determination (R^2) and Chi Square (χ^2) the selected drying model was the one by Midilli *et al.* (2002), with R^2, χ^2 and RMSE values of 0.9487, 0.4278 and 0.1723 respectively. The model coefficients were determined for drying air temperatures of 40, 45, 50 and 55°C. It was found that the predicted and experimental data agreed satisfactorily with R^2 and RMSE values of 0.9225-0.9786 and 0.0325-0.0750 respectively. A computer simulation model was developed to predict moisture ratio at a given drying time.

Keywords: *forced convection, drying model, model coefficients, shelled maize, computer simulation model*

Cite This Article: Booker Osodo, Daudi Nyaanga, and Joseph Muguthu, "Selection and Verification of a Drying Model for Maize (*Zea mays L.*) in Forced Convection Solar Grain Dryer." *American Journal of Food Science and Technology*, vol. 5, no. 3 (2017): 93-100. doi: 10.12691/ajfst-5-3-4.

1. Introduction

A great proportion of crop is often lost between harvesting and consumption, the problem of post-harvest loss being particularly significant in developing countries. In these countries, such losses are estimated to be of the order of 40%, but can rise to being as high as 80% under very adverse conditions [1]. According to [2], incidents of post-harvest food loss in Kenya have been estimated at 30%, and can rise to as high as 100% with the advent of afflotoxin. A significant percentage of the losses are related to improper and, or untimely drying of foodstuffs such as cereal grains, meat, tubers and fish [1,2]. Moist and partly moist crop is prone to fungus infection, which renders it unusable. High moisture content also encourages loss due to attacks by insects, pests and increased respiration [3,4].

[5] reported that loss of crop occurs in the field (15%), during harvesting (13-20%), processing and also in storage (15-25%). Post-harvest loss of crop may be attributed to different causes. Pests, such as large grain borer account for 10-20% loss, while 5-10% of the losses may be attributed to poor storage facilities. Diseases, on the other hand, contribute to 5% of post-harvest crop loss [6]. Drying of maize to below 13.5% moisture content increases storage life and maintains quality by decreasing growth of fungi and insect infestation during storage. It also prevents germination, reducing post-harvest loss and hence ensuring more food is available for the growing world population [2,4]. Grain drying may be carried out using different sources of energy. However, solar energy is preferred to other alternative sources of energy such as wind and shale since it is abundant, inexhaustible and nonpolluting [7].

Solar dryers may be classified into two broad categories, on the basis of the mode of air circulation. Passive solar dryers, also called natural convection or natural circulation dryers, depend for their operation entirely on solar energy. Solar heated air is circulated through the crop by buoyancy forces or a result of wind pressure, acting either singularly or in combination [8,9]. Passive solar dryers have one major limitation, being inadequate air flow leading to low drying rates and crop rotting. Active solar dryers, also called forced convection or hybrid solar dryers, use a fan to enhance circulation of the solar heated air [10]. Optimum air flow can therefore be provided throughout the drying process to control temperature and moisture content of the air [8,9].

According to [11,12], modeling of solar drying curves is generally to elaborate a function verifying eq. (1).

$$X_r = f(t) \tag{1}$$

In this equation, X_r is moisture ratio given by eq. (2) or (3)

$$X_r = \frac{X - X_{eq}}{X_{cr} - X_{eq}} \tag{2}$$

$$X_r = \frac{X - X_{eq}}{X_0 - X_{eq}} \tag{3}$$

(X is the moisture content at any instant and X_0 the initial moisture content while X_{cr} and X_{eq} represent the critical and equilibrium moisture contents, respectively).

Moisture ratio may, however, be simplified to eq. (4) since relative humidity of the drying air continually fluctuates during solar drying [13].

$$X_r = X / X_0. \tag{4}$$

Table 1 shows some of the models that have been developed to predict moisture ratio at any given drying time, for cereals such as corn, wheat and rice.

Various statistical methods may be applied for selecting the most suitable model for describing the drying behavior of a product under specific conditions. They are used as a means of comparing experimental data for the drying behavior of the product to those predicted by the drying model [14].

One of these statistical tools is the Coefficient of Determination (R^2), which varies between 0 and 1, and is obtained from eq. (5). The closer the R^2 value is to 1, the closer the relationship between the experimental and model predicted values [14,15,16,17]. Modelling Efficiency (EF) [eq.(6)] is another tool, its value tending towards 1 for a good fit. Root Mean Square Error (RMSE) or Root Mean Square Deviation (RMSD) is yet another tool, obtained from eq. (7), and for which values should tend to 0 for the best fit Reduced chi-square (χ^2), shown in eq. (8), is the mean square of deviations between experimental and predicted values. The lower its value, the better the goodness of fit [12,14].

$$R^2 = \frac{(\sum MR_{\exp} MR_{pre})^2}{\sum MR_{\exp}^2 \sum MR_{pre}^2} \tag{5}$$

(Where SS_{Res}= Residual sum of Squares, SS_{To}= Total sum of squares, $SS_{Res} = \sum(y_i - \hat{y}_i)^2$, $SS_{To} = \sum(y_i - \bar{y})^2$, $\hat{y}$ = predicted value &$\bar{y}$ the mean value).

$$EF = \frac{\left[\begin{array}{l}\sum_{i=1}^{N}(MR_{i,\exp} - MR_{i,\exp_{mean}})^2 \\ -\sum_{i=1}^{N}(MR_{i,pre} - MR_{i,\exp})^2\end{array}\right]}{\sum_{i=1}^{N}(MR_{i,\exp} - MR_{i,\exp_{mean}})^2} \tag{6}$$

$$RMSE = \left\{\frac{1}{N}\sum_{i=1}^{N}(MR_{\exp,i} - MR_{pre,i})^2\right\}^{1/2} \tag{7}$$

$$\chi^2 = \frac{\sum_{i=1}^{N}(MR_{\exp,1} - MR_{pre,i})^2}{N-n} \tag{8}$$

(N and n represent the number of observations and constants respectively, while $MR_{\exp,I}$ is the experimental moisture ratio and $MR_{pre,i}$ the predicted moisture ratio).

Table 1. Mathematical Models for Drying Curves

S/ No	Model Name	Model Equation	Source	Crop
1	Page	$X_r = \exp(-kt^n)$	Page(1949)	Shelled corn
2	Wang &Singh	$X_r = 1 + at + bt^2$	Wang & Singh(1978)	Rough rice
3	Two Term	$X_r = a\exp(-k_0 t) + b\exp(-k_1 t)$	Yi *et al*.(1980)	Corn
4	Modified Page	$X_r = \exp\left(-(\mathrm{kt})^n\right)$	White *et al*.(1981)	Pop corn
5	Verma*et al.*	$X_r = a\exp(-kt) + (1-a)\exp(gt)$	Verma*et al*.(1985)	Rice
6	Diffusion approach	$X_r = a\exp(-kt) + (1-a)\exp(-kbt)$	Kassem(1998)	Wheat
7	Midilli*et al.*	$X_r = a\exp(-kt^n) + bt$	Midilli*et al*.(2002)	Mushoom

Source: (Lahsasni *et al*. 2004).

Table 2. Drying Models with Model Constants for Maize

Model No	Model Name	Model Constants
1	Page	k= 0.1248
		n = 1.0440
2	Wang &Singh	a = 0.09199
		b = 0.00210
3	Two Term	k_o= 0.1171
		k_1= 0.1239
		a=-1.989
		b=3.002
4	Modified Page	k=0.0515
		n=1.0932
5	Verma *et al.*	a=2.089
		k=0.1324
		g=0.1281
6	Diffusion approach	a=7.436
		b=0.9879
		k=0.1267
7	Midilli *et al.*	k=0.106
		n=1.137
		a=0.988
		b=0.001084

Source: Meisami and Rafiee (2009).

Various researchers have applied these statistical tools to select the best fitting drying models for different products. For example, using a forced convection solar dryer for drying maize, [18] found, based on RMSE, R^2 and χ^2, that the best fitting drying model was the one by [19]. Drying constants for maize in the various models are shown in Table 2.

[20] carried out drying experiments on quercus fruits at temperatures of 50, 60 and 70°C and air velocities of 0.5 and 1 m/s. From among five models investigated, the experimental drying curve best fitted the Page model. The best fit was based on R^2, χ^2 and RMSE values. They also reported that model constants depend on the variables studied. Using R^2 and χ^2 to fit selected drying models to the drying curve for banana fruit, Silva *et al*. (2014) also found that the Page model gave the best fit. [18] however, used RMSE, χ^2 and modelling efficiency (EF) for selecting the best fitting drying model for thin layer apple drying. Experiments were carried out at temperature ranges of 40 to 80°C, air velocities 0.5, 1 and 2 m/s as well as slice thicknesses of 2, 4 and 6 mm. The model by [19] gave the best fit.

This study tested selected models to identify the one that best describes the drying curve for maize. R^2, RMSE) and x^2 were used to determine the best fitting model. Once identified, the coefficients for the selected model were determined. Finally, a computer simulation program for predicting variation of moisture ratio with time was developed. The findings will help in enhancing quality of the dried maize since drying will be under controlled air velocity and temperature conditions. Contamination, cracking and discoloration of grain will thus be prevented.

1.1. Experimental Set-up

The study was carried out in Njoro, Nakuru County, Kenya. Njoro is located 18 km South West of Nakuru town. It lies at an altitude of 1800m above sea level, and experiences temperature ranges between 17-22°C. Nakuru County is a moderate to high solar energy potential area. The amount of available solar energy is season dependent, with the December-February season receiving the highest amount of insolation of 678 kWh/m^2.During the experimental sessions, insolation ranged between 280 – 1080 W/m^2.

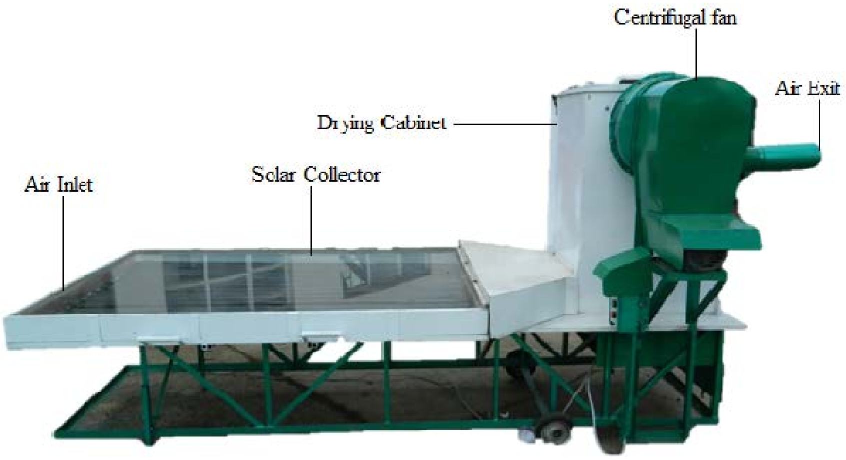

Figure 1. Side View of Experimental solar dryer

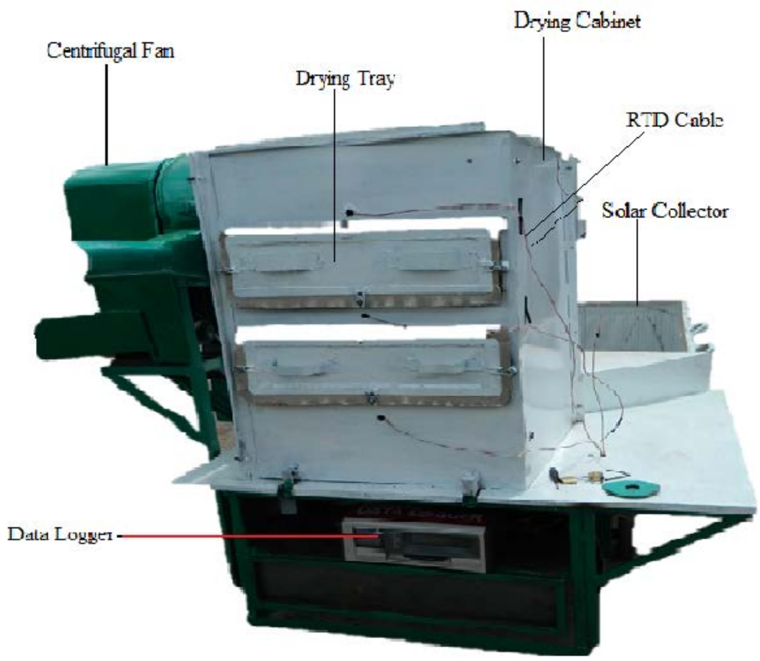

Figure 2. Rear View of Experimental Solar dryer

The experimental solar grain dryer (Figure 1 & Figure 2), consisted of a flat plate solar collector and a drying cabinet with a 0.7 kW centrifugal fan to force the air into the dryer. It had a collector area of 1.2 m x 1.8 m and an air vent of height 0.1 m. The absorber plate comprised of black painted corrugated iron sheet. The glass cover was of 5 mm thick glass, the air heater sides and back plate being made of 5 mm thick ply wood. The drying chamber had dimensions 0.5 m x 0.5 m x 1 m, with a 1.25 mm MS sheet metal casing. Its sides consisted of double plates, 40 mm apart with polystyrene in between for lagging. A centrifugal fan was fixed at the upper section of one side. The plenum chamber was covered with a perforated plate 200mm from the bottom of the drying cabinet. The drying tray, whose sides were of 1.25 mm MS sheet metal, with bottoms of wire mesh was 100 mm above the perforated plate.

1.2. Testing and Verification of Drying Model

1.2.1. Selection and Testing of Drying Model

Drying was carried out over a period of time, retrieving a sample every 20 minutes and using it to determine moisture content, which was done according to ASAE Standard S352.2 [21], which describes the procedure for measuring moisture in unground grain and seeds. According to these standards an electrical balance with accuracy of 0.001 g, a desiccator that is airtight and contains a suitable desiccant, and a forced-draft or gravity convection oven are used. The oven should be well insulated and maintain uniform heating inside the oven and be accurate to plus or minus 5°C. A minimum of 15 g of grain is dried in the oven for a period depending on the grain. For corn, the drying period is 24 hours, followed by drying at 1 hour intervals till constant mass is achieved. Wet basis moisture content X_w, was determined from eq. (9),

$$X_w = \frac{m_w}{m_{wg}} X100 \tag{9}$$

(m_w refers to mass of water evaporated while m_{wg} and m_{dg} refer to total weight of wet grain and dry grain, respectively).

Moisture ratio was thereafter calculated using eq. (4). This was done for a grain layer thickness and air velocity identified of 0.04 m and 0.408 m/s respectively. Data of variation of moisture ratio with time was used to produce a scatter plots using excel 2013. The regression equation for moisture ratio, along with selected drying models, were tested to select the best fit for the experimental drying data. This was done using coefficient of determination (R^2), χ^2 [eq. (5)] and RMSE [eq. (6)]. The model constants used were adopted from similar experiments carried out for maize under similar climatic conditions [22]. The best fitting model or equation was thus adopted for use in predicting drying time. It was used to develop a computer simulation model for predicting drying time for given moisture content or moisture ratio.

1.2.2. Determination of Drying Coefficients

Studies to determine drying constants for spearmint showed that the constants varied as a function of temperature [23]. It was therefore necessary to validate the constants before they could be applied in the computer simulation model.

0.04 m thick maize grain was dried for three hours at 40°C, at an air velocity of 0.408 m/s, determining the moisture content every 30 minutes using the oven drying method. The variation of moisture ratio with time during the drying process was used to plot the experimental drying curve. The drying curve [19] was then customized in the software MATLAB R2012B, and the experimental data for variation of moisture ratio at 45 °C fitted to it, using Coefficient of Determination (R^2) and RMSE to determine the best fit. The values of the Midilli coefficients were then determined using the software. The same was repeated for the same grain layer thickness dried at the same air velocity, but at varying temperatures (45, 50 and 55 °C).Thus, the drying constants at 40, 45, 50 and 55 °C were determined for use in the computer simulation model.

1.2.3. Verification of Drying Model

A computer simulation model to predict moisture ratio for a given drying time was developed. The input parameters were drying time, as well as the constants a, b, k and n. the output parameter was moisture ratio, X_r which could then be used to determine moisture content for known initial moisture content. Figure 3 shows a flow chart for the computer simulation model. The best fitting model equation obtained in sections 3.2.1 and the model constants determined in 3.2.2 were used in the model. The program Visual Studio 2012 was used in the model development, with application of the language C#.

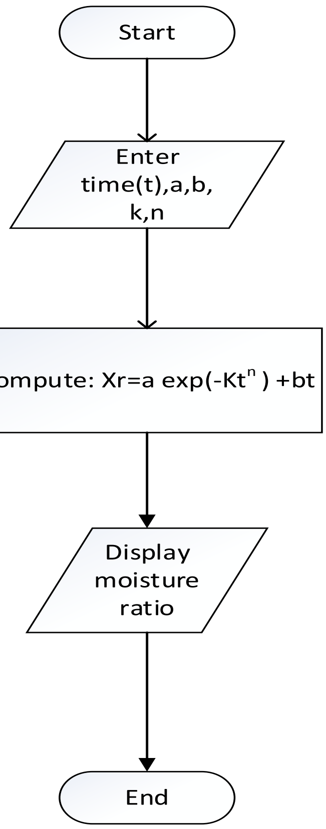

Figure 3. Flow Chart for Computer Simulation Model

1.2.4. Model Validation

To validate the computer simulation model, its results were compared to experimental results. R^2 and RMSE were used to test the reliability of the model.

2. Results and Discussion

2.1. Drying Model

2.1.1. Best Fitting Model

Figure 4 is a graphical variation of grain moisture content and moisture ratio with time when dried for a period of four hours at 20 minutes interval. Both moisture content (X) and moisture ratio (X_r) were found to be decreasing gradually and followed the same trend. The regression equations for X and X_r are shown in eqs. (10) and (11). These are polynomials, and were selected due to their high R^2 values of 0.9857 and 0.9855 respectively.

$$X = 0.00009t^2 - 0.1096t + 38.446 \quad (10)$$

$$X_r = 0.000003\mathbf{t}^2 - 0.003\mathbf{t} + 1.0245. \quad (11)$$

Table 3 shows χ^2 , R^2 & RMSE values for the models that were tested to select the one that would best fit the curve for prediction of moisture rate at different drying times for maize. It was found, based on R^2 values (the higher, the better), that the one by [19] was best. This was confirmed by the values of χ^2 and RMSE (the lower the better).This was in agreement with the findings of other researchers [18]. However, it was noted that based on all the three statistical tests, the experimental regression equation would be best in predicting moisture ratio during the drying of maize. These findings will enable production of good quality product from the drying process. Drying under controlled air velocity and temperature will prevent cracking and discoloration of grain, which would compromise grain quality.

Table 4 presents the model [19] coefficients with 95 % confidence bounds, determined using MATLAB R2012B, as well as the goodness of fit values for R^2 and RMSE. It may be seen that the values changed with temperature.

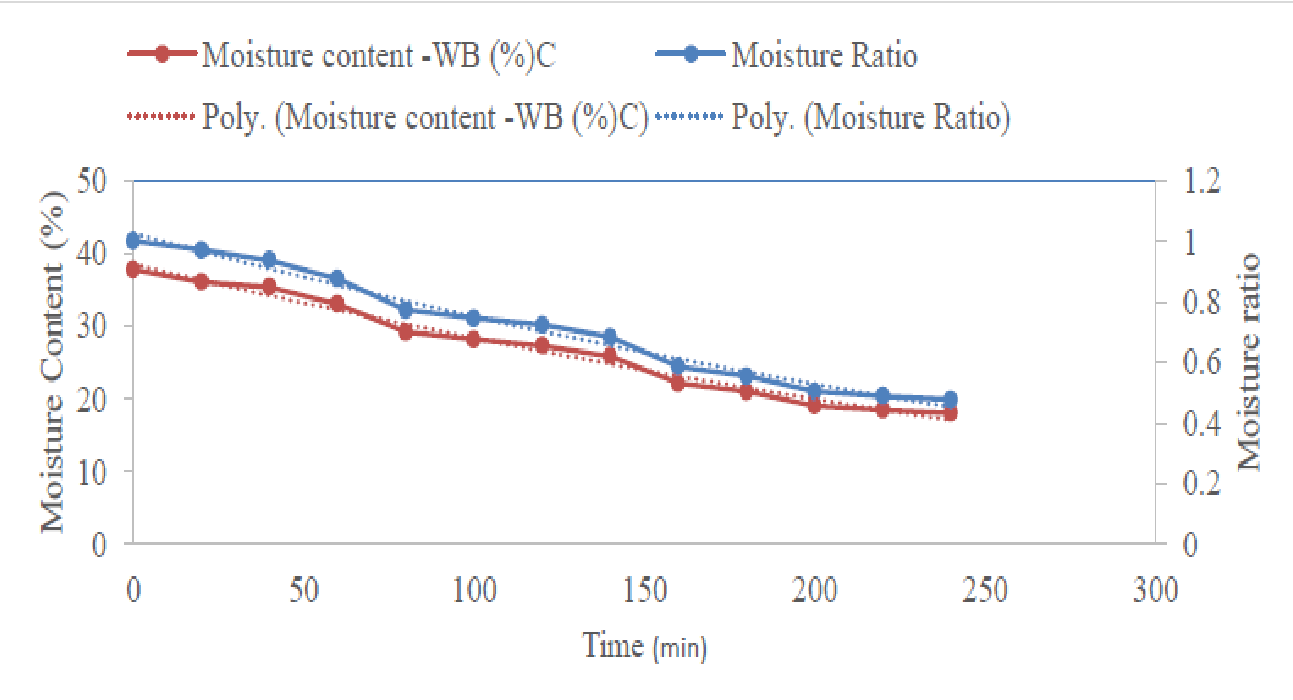

Figure 4. Variation of Moisture Content & Moisture Ratio

Table 3. χ^2, R^2 **& RMSE for Different Models**

Model No	Model Name	Equation	χ^2	R^2	RMSE
1	Page	$X_r = \exp(-kt^n)$	0.5981	0.2745	0.2038
2	Two Term	$X_r = a\exp(-k_0 t) + b\exp(-k_1 t)$	0.5980	0.2730	0.2037
3	Modified Page	$X_r = \exp[-(kt)^n]$	0.5193	0.4862	0.1899
4	Midilli *et al.*	$X_r = a\exp\left(-kt^n\right) + bt$	0.4278	0.9487	0.1723
5	Regression Equation	$X_r = 0.00009t^2 - 0.109t + 38.446$	0.0008	0.9857	0.0243

Table 4. Midilli Coefficients and Goodness of Fit Values

Temperature (°C)	Midilli coefficient	R^2 value	RMSE value
40	a =1 b = 0.0064 k = 0.0003 n=0.8719	0.6159	0.1328
45	a =1 b = 0.0693 k = -0.0010 n=0.3476	0.9915	0.0233
50	a =1.0090 b = 0.0069 k = 0.0024 n=1.021	0.6237	0.1314
55	a =0.9812 b = 8.258 k = -0.0022 n= -io5.318	-4.824	0.5059

2.1.2. Verification of the model

The selected model was verified by comparing the moisture ratios predicted by it to those obtained experimentally. Table 5 shows the variation of experimental and predicted moisture ratios with time at different drying air temperatures, when 0.04 m grain layer thickness was dried using air at a mass flow rate of 0.102 kg/s.

Figure 5 presents a scatter plot for predicted and experimental moisture ratios for 40°C temperature, and shows that there is considerable agreement between the values. They band closely around the linear trend line, with an R^2 value of 0.9909. Similar results were observed for 45, 50 and 55°C.

Figure 6 shows that predicted and experimental moisture ratios vary closely with time, again confirming that the selected model may be used to predict moisture ratio at different drying times.

R^2 and RMSE values (Table 6) also showed a good fit between predicted and experimental results. It may therefore be concluded that the selected model can be used to satisfactorily predict moisture contents and ratios during the drying of maize grain.

Table 5. Predicted and Experimental Moisture Ratios at different Temperatures

Moisture Ratio at 40(°C)		Moisture Ratio at 45(°C)		Moisture Ratio at 50(°C)		Moisture Ratio at 55(°C)	
Predicted	Experimental	Predicted	Experimental	Predicted	Experimental	Predicted	Experimental
1	1	1	1	1.009	1	1	1
0.8915	0.908	0.7677	0.838	0.8813	0.973	0.9144	0.897
0.8132	0.83	0.6900	0.769	0.7885	0.859	0.8477	0.808
0.7482	0.8	0.6281	0.722	0.7276	0.774	0.7809	0.713
0.6927	0.74	0.5735	0.674	0.6929	0.739	0.7142	0.703
0.6446	0.673	0.5233	0.599	0.6795	0.652	0.6474	0.647
0.6025	0.639	0.4761	0.536	0.6832	0.62	0.5807	0.609

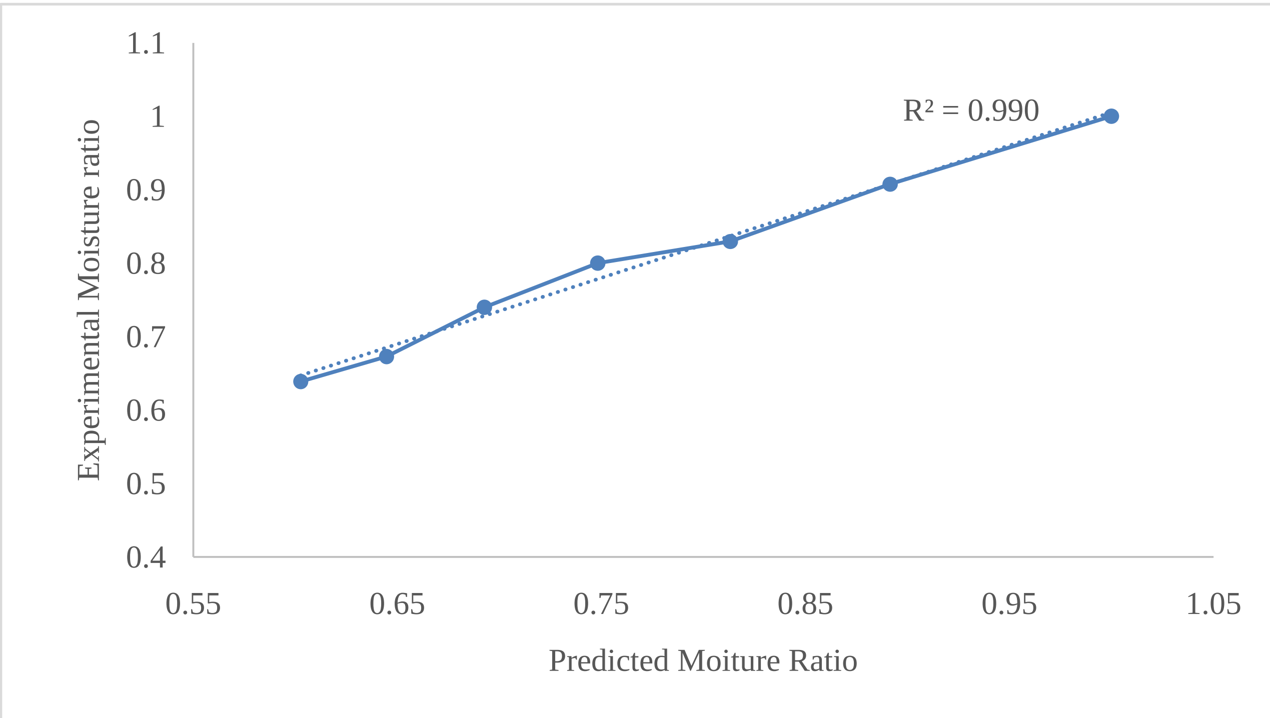

Figure 5. Predicted and Experimental Moisture Ratios

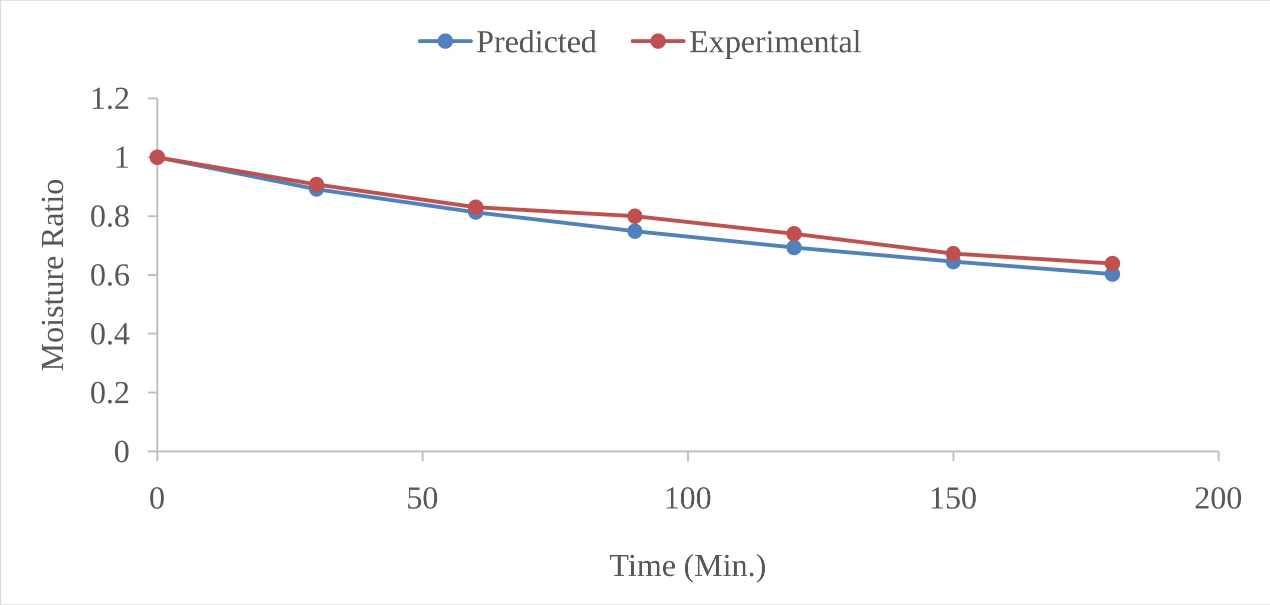

Figure 6. Curves for Predicted and Experimental Moisture Ratio at 40°C

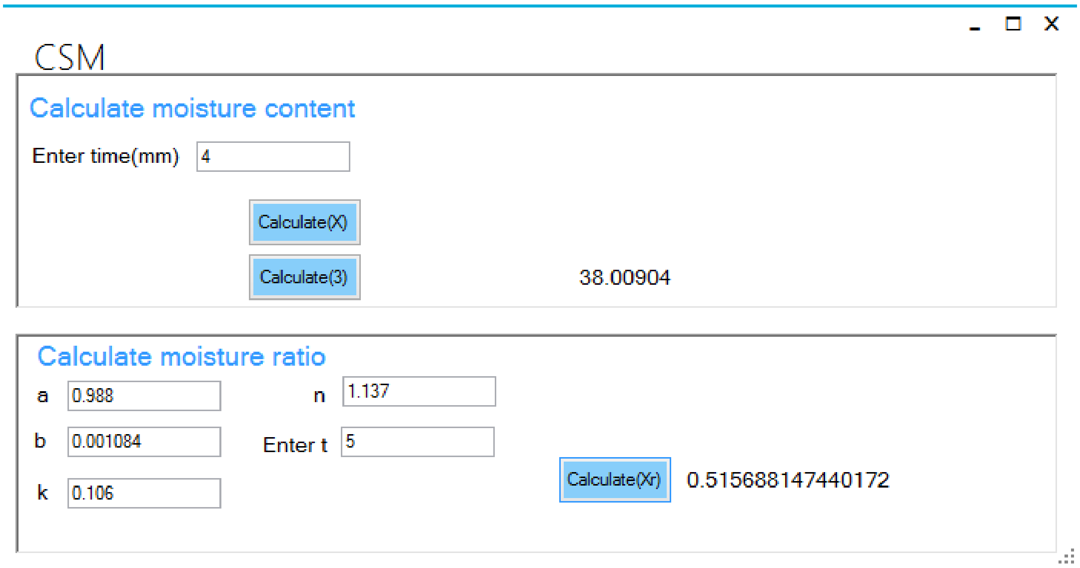

Figure 7. Computer Simulation Model for Moisture Ratio

Table 6. R^2 and RMSE values for Predicted and Experimental Moisture Ratio Curves

Drying Temperature (°C)	R^2 value	RMSE value
40	0.9225	0.0330
45	0.9609	0.0325
50	0.9757	0.0567
55	0.9378	0.0325

2.1.3. Computer Simulation Model

Figure 7 is an image of the computer simulation model that may be used for determining the moisture ratio at any given time as long as the constants a, b, k and n are known.

3. Conclusions

Various drying models were tested to select the one that produced the best fit. The selected one was then verified and a computer simulation model developed.

- The drying model that best describes the drying curve was found to be the one by Midilli *et al.* with R^2 and RMSE values of 0.9487 and 0.1723 respectively.
- The model coefficients were found to vary with drying air temperature.
- Based on R^2 values (0.9225 - 0.9786) and RMSE values (0.0325 – 0.0750) for predicted and experimental, the drying model was found to satisfactorily predict moisture ratios at 40. 45, 50 and 55°C.

Statement of Competing Interest

The authors have no competing interest.

Funding

This research received funding from the National Council for Science, Technology and Innovation (NACOSTI), Kenya.

Acknowledgements

The authors would like to acknowledge the National Council for Science, Technology and Innovation (NACOSTI), Kenya for funding the research.

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