IOP Conference Series: Materials Science and Engineering

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Mathematical modeling of the moisture ratio during drying of Yam (*Dioscorea rotundata*) in a hot air dryer

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Abstracts
Drying is one of the major unit operation in food industry and it kinetics data is required for optimization. The aim of this study was to evaluate the effect of air temperature (50, 60, and 70^{O}C), air velocity (0.5, 1, and 1.5 m/s), and slice thickness (3, 6, and 9 mm) on the moisture ratio of yam slice during drying. Ten (10) different empirical models were used in fitting the experimental moisture ratio data, the prediction performance was evaluated with sum of square error (SSE), coefficient of determination (R^2) and root mean square error (RMSE). The model fitting shows that the Two term model was most performed based on R^2, SSE, and RMSE value. This result can be use to control the drying systems for yam slice.

Key words: moisture ratio, yam, mathematical model, hot air drying, heat and mass transfer

1. Introduction

Yam is tuberous root that serve as a foremost source of protein and calorie in the diet in West Africa. It is starchy and naturally cultivated in warm regions. It serves as staple food for more than 100 million around the globe [1, 2]

White yam (*Dioscorea rotundata*) is among the most economically viable yam specie in West Africa particularly Nigeria [3]. However, its classified as highly perishable food based on its moisture content of about 70 % wet basis thus making its long-term storage a challenge [4].

Drying one the human ancient method for food preservation which and it involves concurrent heat and mass transfer resulting to a complex thermal process [5]. Dried white yam is useful for production of instant yam flour and resistant starch extraction [6]. Some of the drying technologies used either singly or combined for food processing are the use of hot air, microwave, vacuum and infrared [7]. Using hot air-drying method is advantageous as it is highly efficient for removal of surface water with lower operational cost [8, 7]. The use of mathematical models to explain the drying process of many food products has attracted the interest of several researchers for decades [7]. Some of the related research works includes; Falade *et al.,* [9], effect of pretreatment and air temperature on the drying process for *Dioscorea rotundata* and *Dioscorea alata*, but did not model the moisture ratio, Ju *et al.,* [10], studied the drying process at different relative humidity conditions for yam slices, Pornpraipech *et al.,* [11] studied the drying performance of cassava chips based on the influence of shape and temperature, Srikanth *et al.,* [6], studied the drying kinetic and rehydration kinetic for elephant foot yam at different temperatures. There has been prior information on the drying characteristics of *Dioscorea rotundata,* but there is little or no information on the mathematical modeling of the drying

IOP Conf. Series: Materials Science and Engineering 1107 (2021) 012062 doi:10.1088/1757-899X/1107/1/012062

kinetic of yam as a function of temperature, air velocity and slice thickness using convective hot air drier. The kinetic modeling is required for prediction and control of the drying process in food industry. Therefore, the aim of this present work was to predict the drying kinetic of *Dioscorea rotundata* using ten frequently used mathematical models.

2. Experimental Methods

The yam tubers used were procured in January, 2019 at an open market and identified at Landmark University Teaching and Research Farm, Omu-Aran, Kwara State, Nigeria. The yam tubers were carefully sorted out from damaged tubers. AOAC [12] method was used to determine the initial moisture content of the yam slice prior to the commencement of the drying operation. The moisture content ranged between 66.00 to 67.40 % wet basis. Yam tubers were washed under running water, drained, manually peeled and sliced to specific rectangular shapes.

2.1. Drying procedure

Hot air drier developed by Agricultural and Biosystems Engineering department, Landmark University was used for the study. In other to stabilize the drying environment, the drying was run empty for 30 mins.

In the first hour of the experiment, yam samples were removed at 10 mins interval, followed by 30 mins interval for 2 hours, 1 hour interval for 3 hours, and 2 hour for successive drying times till a constant weight was obtained [13]. Five (5) replicates were used and the mean values for drying experiment were obtained.

2.2. Hot air dryer description

The hot air drier used consist of a temperature and air velocity control system, axial fan, hot air production chamber, and a moist air chimney. The temperature and air velocity controller was used to set the temperature and air velocity. The drying temperature of the chamber was measured with a thermocouple (M6 Screw thermocouple KE PT100 type). It triggers off the heater once the set temperature is reached. The air velocity used ranged between 0.5 – 1.5 m/s, while the temperature used was between 50 to 70^{0}C. During the experiment the samples were weighed manually with an analytical weighing balance (accuracy ±0.0001 g) (AND GR-200, Japan).

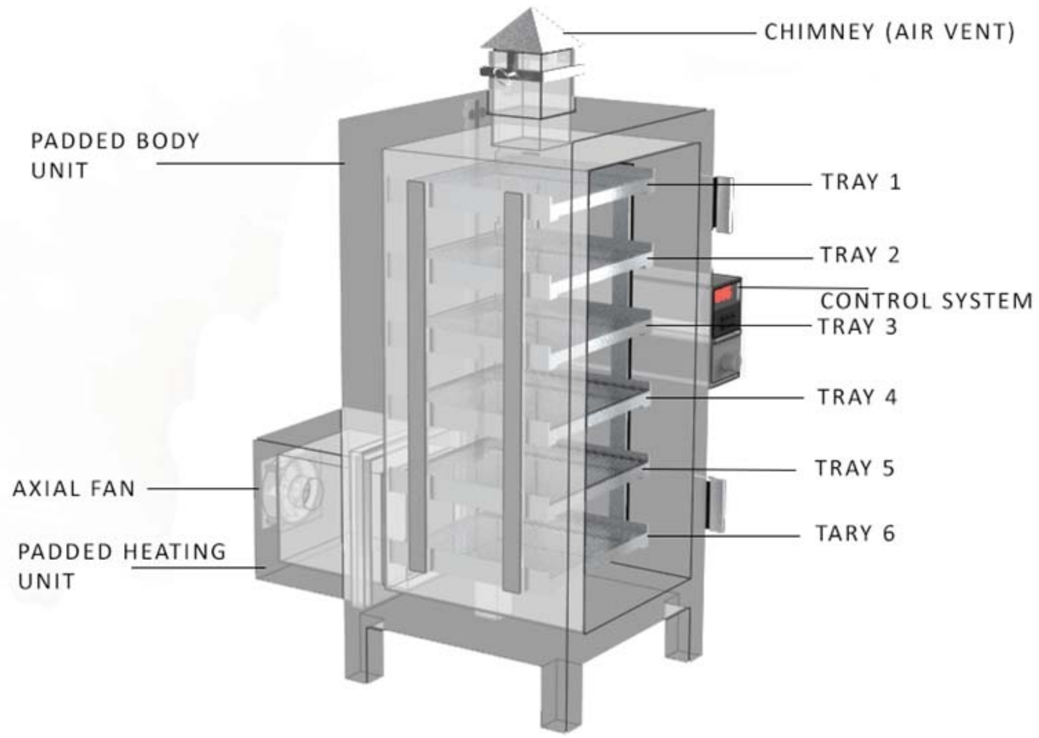

Figure 1: 3-D view of the fabricated drier

2.3. Mathematical modeling of the drying kinetics

Drying kinetic (moisture ratio) predict other parameters in the drying process [7].

Calculation of Moisture ratio (MR) for yam slices was done using Equation (1).

$$MR = \frac{M_t - M_e}{M_o - M_e} \tag{1}$$

Where M_t represents the moisture content of the yam slice at any time during drying (kg water/kg dry matter), M_e is the moisture content when the yam slice attains a constant weight (kg water/kg dry matter), M_o represent the moisture content before commencing the drying operation (kg water/kg dry matter).

The fitting for the drying data as documented Table 1 was done using ten (10) diverse thin- layer drying models, the choice was based to their applicability to wide range of drying conditions and good description of moisture transfer [14]. To validate the quality of fit; the coefficient determination (R^2), sum of square error (SSE), root mean square error (RMSE) parameters were used for calculation as shown below [15].

$$SSE = \sum_{i=1}^{n} (MR_{exp,i} - MR_{pre,i})^2 \quad (2)$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N} (MR_{pre,i} - MR_{exp,i})^2\right]^{1/2} \quad (3)$$

$$R^2 = 1 - \left[\frac{\sum_{i=1}^{N} (MR_{pre,i} - MR_{exp,i})^2}{\sum_{i=1}^{N} (MR_{pre,i} - MR_{exp,i})^2}\right] \quad (4)$$

Where $MR_{pre,i}$, $MR_{exp,i}$ = predicted and experimental moisture ratio respectively; N = number of observations considered, z = number of constants. These fitting tools were used to determine the best model which describes the drying characteristics of the yam slices. The model having the highest R^2, least SSE and RMSE was suggested as the best model for the drying kinetic of yam [16].

Table 1: Emperical models tested for the moisture ratio of yam slices

S/N	Model name	Type	References
1	Page	$MR = \exp(-kt^n)$	[17]
2	Henderson and Pabis	$MR = a\exp(-kt)$	[18]
3	Lewis	$MR = \exp(-kt)$	[19]
4	Modified page	$MR = \exp(-(kt)^n)$	[20]
5	Logarithmic	$MR = a\exp(-kt) + c$	[21]
6	Approximation of diffusion	$MR = a\exp(-kt) + (1-a)\exp(-kbt)$	[22]
7	Two term	$MR = a\exp(-gt) + b\exp(-ht)$	[22]
8	Wang and Singh	$MR = 1 + at + bt^2$	[16]
9	Fourth degree polynomial	$MR = a + bt + ct^2 + dt^3 + et^4$	[19]
10	Midilli	$MR = \exp(-kt^n) + bt$	[17]

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3. Results and discussion

Table 2: Selected model with their Statistical analysis at various air temperatures, velocities and thickness levels for yam slice

Air temperature (^{0}C)	Air velocity (m/s)	Slice thickness (mm)	Model name	Coefficient of Determination (R^2)	Root mean square error (RMSE)	Sum of Square error (SSE)
50	0.5	3	Approximation of diffusion	0.9996	0.006983	0.0009752
			Two term	0.9996	0.007156	0.0009729
50	0.5	6	Two term	0.9949	0.02512	0.01262
50	0.5	9	Logarithmic	0.997	0.02108	0.009773
			Two term	0.9967	0.02252	0.01065
50	1	3	Two term	0.9995	0.009147	0.001506
50	1	6	Two term	0.9996	0.007537	0.001079
			Logarithmic	0.9996	0.007411	0.001099
			Henderson and Pabis	0.9996	0.007267	0.001109
50	1	9	Two term	0.9936	0.03184	0.02028
50	1.5	3	Midilli	0.9992	0.01047	0.001972
50	1.5	6	Approximation of diffusion	0.9955	0.02371	0.01068
			Two term	0.9955	0.02436	0.01068
50	1.5	9	Approximation of diffusion	0.9984	0.01465	0.004294
			Two term	0.9984	0.01497	0.004257
60	0.5	3	Two term	0.9941	0.03536	0.0225
60	0.5	6	Approximation of diffusion	0.9989	0.01232	0.003034
60	0.5	9	Two term	0.999	0.01204	0.002897
60	1	3	Two term	0.9962	0.01934	0.006358
60	1	6	Henderson and Pabis	0.9998	0.00482	0.0004647
			Logarithmic	0.9998	0.004933	0.0004624
			Two term	0.9998	0.005081	0.0004647

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60	1	9	Henderson and Pabis	0.9971	0.02133	0.009554
			Logarithmic	0.9972	0.02149	0.009235
			Two term	0.9972	0.02204	0.009229
60	1.5	3	Page	0.9963	0.01916	0.00661
			Modified page	0.9963	0.01916	0.00661
			Two term	0.9963	0.02026	0.00657
			Midilli	0.9963	0.01972	0.00661
70	0.5	3	Approximation of diffusion	0.9998	0.004027	0.0002919
			Two term	0.9998	0.004052	0.0002791
70	0.5	6	Two term	0.9992	0.009812	0.001733
70	0.5	9	Approximation of diffusion	0.998	0.01614	0.005211
70	1	3	Page	0.9982	0.01537	0.004252
			Modified page	0.9982	0.01537	0.004252
			Midilli	0.9982	0.01579	0.004238
70	1	6	Two term	0.9979	0.0177	0.005327
70	1	9	Page	0.9993	0.0102	0.002081
			Modified page	0.9993	0.0102	0.002081
			Midilli	0.9993	0.01038	0.002046
70	1.5	3	Henderson and Pabis	0.9994	0.008435	0.00121
			Logarithmic	0.9994	0.008495	0.001155
70	1.5	6	Logarithmic	0.9993	0.01026	0.001789
70	1.5	9	Page	0.9989	0.01222	0.002838
			Modified page	0.9989	0.01222	0.002838
			Midilli	0.9989	0.01255	0.002833

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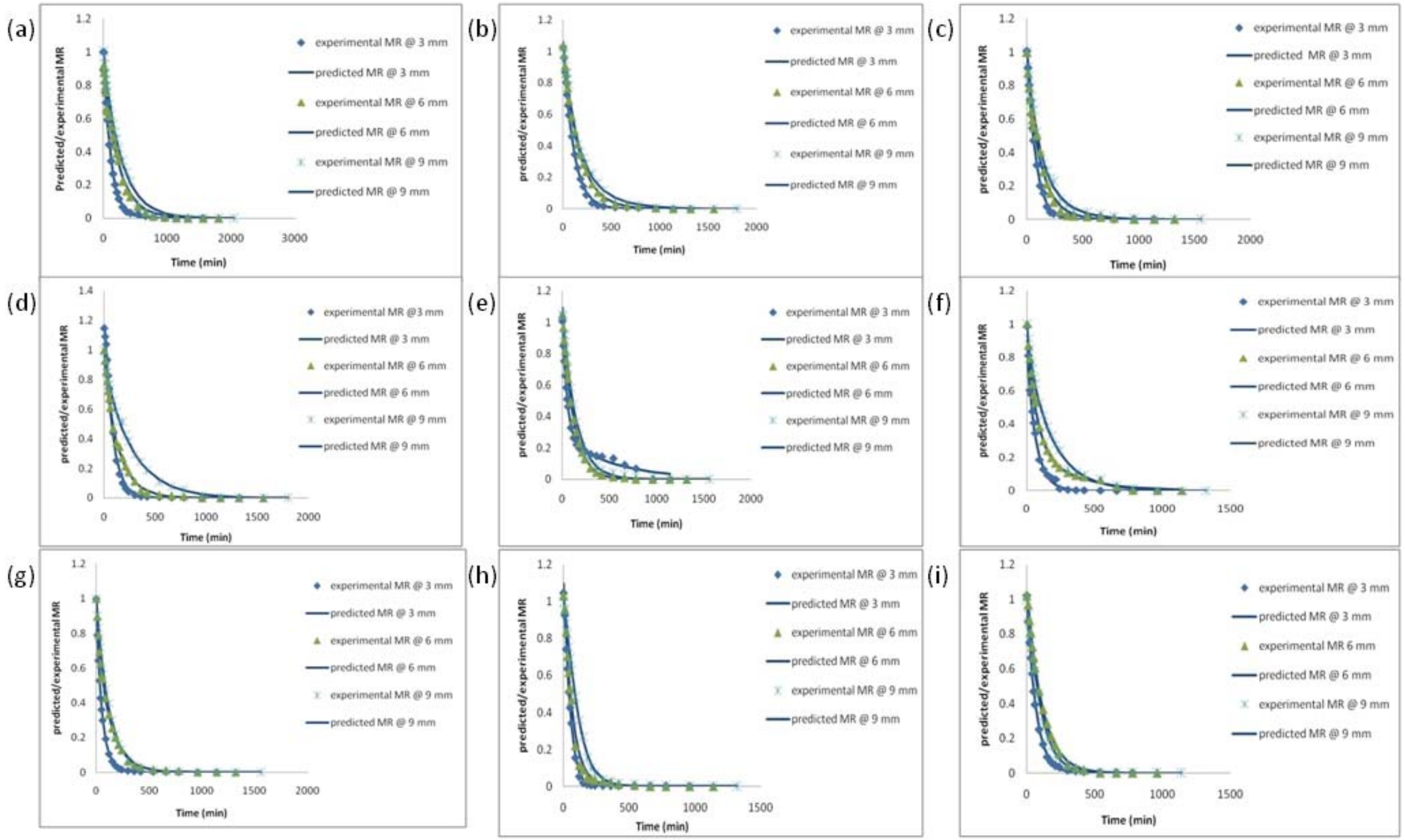

Figure 2: Predicted/experimental moisture ratios versus time using Two term model at temperature and air velocity levels (a: 50^0C and 0.5 m/s, b: 50^0C and 1 m/s, c: 50^0C and 1.5 m/s, d: 60^0C and 0.5 m/s, e: 60^0C and 1 m/s, f: 60^0C and 1.5 m/s, g: 70^0C and 0.5 m/s, h: 70^0C and 1 m/s, i: 70^0C and 1.5 m/s) for 3, 6 and 9 mm yam slice thickness.

3.1. Fitting of drying curves

The best fitted model explains drying behavior of yam slice in a hot air dryer. Ten thin-layer drying models used in fitting the drying data obtained from the experiments are as shown in Table 2. The parameter of the ten models was estimated with the Non-regression analysis. The model with the highest R^2 value and lowest RMSE and SSE values was adopted as the best model in describing the thin layer drying characteristics of yam slice. It was observed in the Table 3a (supporting file) that the various models used performed excellently. However, Table 3 clearly shows certain models exhibited higher degree of fitting performance for the varying drying parameters considered. The Two term drying model had the highest degree of fitting performance due to its wider coverage. The R^2 value for Two term model for all the drying parameters tested was above 0.99, RMSE ranged from 0.004052 to 0.1593, SSE ranged from 0.0004647 to 0.0225. Other drying models like Henderson and Pabis, Logarithmic, Page, Modified page, Approximation of diffusion, Midilli, Fourth degree polynomial, Lewis also performed well with R^2 values all above 0.9. Fig. 2 (a-i) compares the predicted/experimental moisture ratios (MR) with time for yam slices at all the three (3) drying parameters considered; air velocity (0.5 to 1.5 m/s), temperature (50 to 70^{0}C) and slice thickness (3 to 9 mm). Fig. 2 (a-i) shows that the thickness on yam slice had an effect on moisture ratio and drying, there was an increase in drying tie as the thickness increased and a reduction in drying time as the slice thickness reduced. Also an increase in temperature resulted in a decrease in drying time and an increase in moisture ratio. These results agrees with that recorded in literature [23, 24]. Drying occurred during the falling rate period, this result corroborates with that recorded in literature [25, 26]. The prediction using the Two term model showed MR values banded along the experimental data point on the line, which showed the suitability of these models in describing drying characteristics of yam slices.

4. Conclusion

Effect of air temperatures, air velocities, and thickness on the drying kinetics was experimentally investigated using a hot air drier. The drying rate was observed to increase with increased air temperature, air velocity, and decreased slice thickness. The drying kinetics study showed that Two term model was best in accurately describing the drying curve of yam slice amongst others which performed satisfactorily with R^2 close to 1, lowest SSE and RMSE values. The Two term model can therefore be used in predicting and describing the drying process of yam. This result would help us understand the drying behavior of yam in a convective dryer.

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