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Mathematical Model of Thin-Layer Drying Process in a Plantain Sample

[1]Oforkansi, B.C, Oduola, M.K.
Department of Chemical Engineering, University of Port Harcourt, Nigeria.
[1]E-mail: benjaminoforkansi@yahoo.com

ABSTRACT : This research was focused on the selection of the appropriate thin-layer models that best described the drying characteristics of the French horn plantain used in the experiment. The drying of the 5mm thickness size plantain samples occurred at 40°C, 50°C, 60°C and 70°C temperatures until the equilibrium condition was attained. The experimental moisture ratio values at each temperature were fitted to Lewis, Page and Modified-page thin-layer models. The Lewis model has average chi square and average coefficient of determination of 0.0012 and 0.9802 respectively while Modified Page has 0.0009 and 0.9879 respectively. The results show that Page model has the least average chi-square (X^2) value and highest coefficient of determination (R^2) value of 0.0008 and 0.9922 respectively. Therefore, Page model best described the drying characteristics of the plantain sample within 40°C- 70°C temperature range.

Keywords: Drying, thin-layer models, moisture ratio, chi-square, coefficient of determination

1. INTRODUCTION

Drying as the name implies is a moisture removal technique used in the preservation of high moisture content fruits and vegetables. It is a chemical engineering unit operation involving mass and heat transfer processes. In drying plantain, it is necessary to remove free moisture from the surface and also moisture from the interior of the material. The purpose of reducing water content is to prolong the shelf life of the products by reducing water activity to a level low enough where growth of micro organisms, enzymatic reactions and other deteriorative reactions are inhibited (Khawas et al., 2013). Drying of plantain requires appropriate control in order to preserve the macro and micro nutrients in the food material. Higher drying temperature reduces the drying time but may result in poor product quality such as discolouration, aroma loss, and textural changes. On the other hand, lower temperature may improve the product quality but lowers the drying rate. Generally, the quality of dried product depends on the entire drying conditions; therefore, it is very important to understand the drying process and characteristics of the sample (Khawas et al., 2013). Many researchers have conducted experimental studies on drying process and mathematical modelling of several fruits, leaves and vegetables like broccoli (Pangavhane et al.,1999), red pepper (Doymaz and Pala, 2002), and eggplant (Ertekin and Yaldiz, 2004) . Mathematical modelling of the drying process under different drying conditions is important to obtain better control of the operation and overall improvement of the quality of the final product. Models are often used to study the variables involved in the process, predict drying kinetics of the product and optimize the operating parameters (Karathanos and Belessiotis, 1999).

2. MATERIALS AND METHODS

2.1 Raw material collection and thin layer drying of the sample

French horn plantain variety used in this research was purchased from Agricultural Development Project Farm, Ministry of Agriculture, Rumuodomanya, Obior-Akpor Local Government Area, Rivers State, Nigeria. The French horn plantain samples were transported to Bio-chemistry Laboratory, Abuja Campus, University of Port-Harcourt, Port Harcourt, Nigeria for the study.

The plantain samples were peeled and sliced to 5mm thickness size before the drying. Thin layer drying is assumed so that the initial resistance to moisture movement within the plantain sample is ignored (Satimehin et al., 2010). Three samples of 5mm thickness size of the variety of the plantain were weighed individually by a digital balance of accuracy 300g/0.01g to determine the initial mass of the samples. Thereafter, the samples were put inside the oven dryer (TT-9023A) set at 40°C and the masses were measured continually every 30mins until the equilibrium moisture content condition is attained and the average values recorded. The whole process was repeated at 50°C, 60°C and 70°C in the oven dryer and the weights were recorded.

2.2 Mathematical modelling

Various mathematical modelling equations exist in the literature. Karim and Hawlader (2005) presented a mathematical model for food drying and applied the model to calculate the drying rate of banana. But to determine the moisture ratio as a function of time, three different models obtained from the literature were used. These models were also used by other researchers; Kaleta and Gornicki (2010), Diamante et al. (2010), Dzisi et al. (2012) and Wilton et al.,(2013). The selected mathematical models are Lewis, Page and Modified Page.

2.3 Thin-layer models

The moisture content can be expressed as a function of the free moisture content. Mathematically it is given;

$$\frac{dm_t}{dt} = -k(m_t - m_e) \tag{2.1}$$

$$\int_{m_o}^{m_t} \frac{dm_t}{m_t - m_e} = -k\int_0^t dt \tag{2.2}$$

$$\ln\left(\frac{m_t - m_e}{m_o - m_e}\right) = -kt \tag{2.3}$$

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$$\frac{m_t - m_e}{m_o - m_e} = e^{-kt} = \exp(-kt) \quad (2.4)$$

But $\frac{m_t - m_e}{m_o - m_e} = MR$

Therefore, $MR = \exp(-kt)$ (2.5)

Equation (2.5) gives the **Lewis** thin-layer model. The modification of Equation (2.5) gives the **Page Model**;

$$MR = \exp(-kt^n) \quad (2.6)$$

The modification of the Page Model of equation (3.15) gives the **Modified Page Model**;

$$MR = \exp(-kt)^n \quad (2.7)$$

The models were tested with the experimental data to determine the one that best described the process and the experimental data. The empirical constants for the models were obtained using Microsoft office Excel Solver. In determining the thin layer drying model that best describe the drying data, the values of Coefficient of determination (R^2) and chi-square (X^2),Root Mean Square Error (RMSE) and Standard Error Estimate (SEE) are calculated (Goyal et al., 2007).

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(MR_{pre,i} - MR_{exp,i})^2}{\sum_{i=1}^{N}(MR_{exp,i} - MR_{expmean})^2} \quad (2.8)$$

$$RMSE = \sqrt{\left[\frac{\sum_{i=1}^{N}(MR_{pre,i} - MR_{exp,i})^2}{N}\right]} \quad (2.9)$$

$$X^2 = \frac{\sum_{i=1}^{N}(MR_{pre,i} - MR_{exp,i})^2}{N - z} \quad (2.10)$$

$$SEE = \sqrt{\left[\frac{\sum_{i=1}^{N}(MR_{pre,i} - MR_{exp,i})^2}{N - z}\right]} \quad (2.11)$$

The coefficient of determination (R^2) was considered as one of the main criteria for selecting best drying models (Ozdemir and Devers, 1999; Yaldiz et al., 2001; Erenturk et al., 2004). In addition to coefficient of determination, the goodness of fit was characterised by determining reduced chi-square (X^2) (Demir et al., 2004; Pangavhane et al., 1999). The model with the highest value of R^2 and lowest X^2 indicate the best fit of the model.

3. RESULTS AND DISCUSSION

Tables 3.1-3.4 show the summaries of the regression analyses of the French horn plantain using Lewis, Page and Modified page thin-layer models. The regression parameters, determination coefficient (R^2) and chi-square (X^2) were used to determine the model that best fit the experimental data. The coefficients of the thin-layer models and regression parameters were obtained using the optimization mechanism of Microsoft excel solver. Table 3.1 shows the regression analysis of 5mm thickness size of the French horn plantain at 40°C. The French horn plantain constant, k has values of 0.0038, 0.0037, and 0.0038 for Lewis, Page and Modified Page thin-layer models respectively. The coefficient, n values for Page and Modified Page models are both equal to 1.0059. The R^2 and X^2 values of the French plantain are 0.9900 and 0.0006 for Lewis thin-layer model; 0.9938 and 0.0006 for Page model; and 0.9900 and 0.0007 for the Modified Page model. It can be seen from Table 3.1 that Page model has the highest coefficient of determination and lowest chi-square values. Therefore, Page thin-layer model best fitted and described the experimental data at the drying temperature. The summary of the regression analysis of the 5mm thickness size French horn plantain variety at 50°C is shown in Table 3.2. The model constant, k has values of 0.0042, 0.0114, and 0.0040 for Lewis, Page and Modified Page thin-layer models respectively. The coefficient, n values for Page and Modified Page models are 0.8106 and 0.8106 respectively. The R^2 and X^2 values of the French plantain are 0.9709 and 0.0015 for Lewis thin-layer model; 0.9930 and 0.0006 for Page model; and 0.9894 and 0.0006 for the Modified Page model. It can be seen from the results that Page model also best fitted the experimental data.

Table 3.1: Summary of the regression analysis of 5mm thickness size at 40°C

Model name	Coefficients		Regression Parameters			
	k	n	R^2	RMSE	X^2	SEE
Lewis	0.0038		0.9900	0.0236	0.0006	0.0246
Page	0.0037	1.0059	0.9938	0.2360	0.0006	0.0256
Modified Page	0.0038	1.0059	0.9900	0.0238	0.0007	0.0257

Table 3.2: Summary of the regression analysis of 5mm thickness size at 50°C

Model name	Coefficients		Regression Parameters			
	k	n	R^2	RMSE	X^2	SEE
Lewis	0.0042		0.9709	0.0377	0.0015	0.0395
Page	0.0114	0.8106	0.9930	0.0227	0.0006	0.0247
Modified Page	0.0040	0.8106	0.9894	0.0227	0.0006	0.0247

Table 3.3: Summary of the regression analysis of 5mm thickness size at 60°C

Model name	Coefficients		Regression Parameters			
	k	n	R^2	RMSE	X^2	SEE
Lewis	0.0054		0.9738	0.0399	0.0017	0.2070
Page	0.0120	0.8461	0.9895	0.0308	0.0011	0.0335
Modified Page	0.0054	0.8461	0.9844	0.0308	0.0011	0.0335

Table 3.4: Summary of the regression analysis of 5mm thickness size at 70^{o}C

Model name	Coefficients		Regression Parameters			
	k	n	R^2	RMSE	X^2	SEE
Lewis	0.0067		0.9862	0.0338	0.0012	0.0352
Page	0.0045	1.0775	0.9927	0.0317	0.0012	0.0344
Modified Page	0.0066	1.0775	0.9879	0.0317	0.0012	0.0344

Table 3.3 shows the summary of the regression analysis of the 5mm thickness size of French horn plantain at 60^{o}C. The model constant, k has values of 0.0054, 0.0120, and 0.0054 for Lewis, Page and Modified Page thin-layer models respectively. The model exponent, n values for Page and Modified Page models are both found to be 0.8461. The R^2 and X^2 values are 0.9738 and 0.0017 for Lewis thin-layer model; 0.9895 and 0.0011 for Page model; and 0.9844 and 0.0011 for the Modified Page model. Page model best described the experimental data at this drying temperature. The summary of the regression analysis of the 5mm thickness size of the French horn plantain at 70^{o}C is shown in Table 3.4. The constant, k has values of 0.0067, 0.0045, and 0.0066 for Lewis, Page and Modified Page thin-layer models respectively. The exponent, n values for Page and Modified Page models are 1.0775 and 1.0775 respectively. The R^2 and X^2 values of the French plantain are 0.9862 and 0.0012 for Lewis thin-layer model; 0.9927 and 0.0012 for Page model; and 0.9879 and 0.0012 for the Modified Page model. It can be seen that the Page model has the highest and smallest R^2 and X^2 values respectively. This also makes the Page model the best fitted model for the experimental data. These results are similar to the work by Wilton et al. (2013) on the mathematical models to describe thin-layer drying and to determine drying rate of whole bananas. The Page model was the best to describe the drying characteristics at the temperature range 40^{o}C to 70^{o}C. Also in the work of Dzisi et al., (2012) on the thin-layer modelling of FHIA-21 (Tetraploid Plantain) using hot-air dryer, the Page model also satisfactorily described the drying behaviour of the slices at the temperature range 50^{o}C to 80^{o}C.

4. CONCLUSION

It may be concluded from the research that Page model best described the drying characteristics of the plantain sample within 40^{o}C- 70^{o}C temperature range. Therefore, the moisture ratio and consequently the moisture content at given time within the temperature range may accurately be determined with the Page model.

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