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Modeling the Drying Kinetics of Plantain Chips under Forced and Free Convection

John Iminabo[1], Misel Iminabo[2], Kenneth Dagde[3]
[1, 2, 3]Department of Chemical/Petrochemical Engineering, Rivers State University, Nkpolu Oroworukwo, Port Harcourt, Nigeria
Corresponding Author Email: [1]iminabo.john@ust.edu.ng

Abstract**—***This research was focused on modeling the drying kinetics of plantain chips under forced and free convection conditions, and the selection of the appropriate thin-layer models that best described the drying characteristics of 2cm, 4cm and 5cm thickness of weight 2.5g, 4.4g and 5.1g respectively of plantain chips. The drying of the plantain chips samples was carried out at 50^oC, and 80^oC 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 0.0006 and 0.9879 respectively. The results show that Page model has the least average chi-square (X2) value and highest coefficient of determination (R2) value of 0.0008 and 0.9922 respectively. Therefore, Page model best described the drying characteristics of the plantain chips sample within 50^oC - 80^0C temperature range.*

Keywords**—** *Plantain; Open sun drying; Hot air drying; Mathematical modeling, Effective moisture diffusivity*.

I. INTRODUCTION

Plantain is also known as *Musa Paradisiac;* is one of the most relevant crops in the world. It is a perennial crop belonging to the kingdom *Plantae* and *musaceae* family. It is a staple carbohydrate food planted mostly in the southern part of Nigeria and in the tropical region of the world, and also it can grow in all types of soil provided there is high moisture availability in the soil where it is to be planted. In south western Nigeria, plantain are chipped, dried and milled into fine powder known as plantain flour. The flour maybe constructed in hot water above 80^oC to produce plantain fufu, a dough that is much like that of yam and cassava dough. The meal is most times recommended for diabetics patients as a substitute for other starchy foods. Since plantain has high moisture content, the chips are subjected to drying traditionally using heat from sun but this method requires much time which may result to spoilage, organism attack as well developing off- flavor on storage after drying. Because of these problems, there is need to develop an effective drying technology to convert the product into stable form for industrial and export purposes. The objective of the study is to use mechanical drying system to convert raw plantain chips to dried plantain chips which can be stored and preserved as raw material for production of value added product such as starch and low percentage ethanol. However, to achieve this purpose, there is a need to develop mathematical models which can predict accurately the drying behavior of sample in the dryer. Therefore a mathematical model anchored on drying kinetics which is based on the physical mechanisms of internal heat and mass transfer to the material being dried which controls the process resistance as well as on structural and thermodynamic assumptions must be considered.

Drying represents a technological operation or mechanism which involves the removal of water in solids (with respect to plantain which is a solid). For plantain and other staple food, drying reduces the natural water content to a level which hampers the activities, growth and development of micro-organisms without the destruction of the tissues or depreciation in value. Sun drying under natural convection is widely used as the conventional method of plantain drying. It has a low cost heating source (Doymaz and Ismail, 2011) but having some inherent disadvantages (Kooli *et al*. 2007) such as Slowness of the process, weather uncertainties specially long rainy seasons, high man power costs, large area requirement, insects infestation and contamination with foreign materials are prominent draw backs of sun drying. Nigeria is a tropical country and uses sun drying heavily for reduction of moisture in agricultural materials such as plantain. At present, staple food industry is not in a position to meet the current demand due to the problems associated with sun drying and hence finding alternative drying techniques is a timely need for sustaining the plantain industry.

The drying characteristic curves of most of these food materials were modeled using different drying models such as the Newton model (O'Callaghan *et al*., 1971), Page model (Akpinar *et al*., 2003), Henderson and Pabis model (Karathanos and Belessiotis, 1999), logarithmic model (Yaldiz *et al*., 2001), two term exponential model (Akpinar *et al*., 2003). For example, the page model was found to best describe the drying behavior of potato, red pepper and tomato under hot air drying (Akpinar *et al*., 2003; Simal *et al*., 2005; Doymaz, 2007) while exponential model for mulberry under open sun (Doymaz, 2004) and Newton model for strawberry under solar drying (Beltagy *et al*., 2007) were found to best describe their drying behavior, respectively. plantain being one of the world traded staple food in both fresh and processed form, few researchers have studied the drying of this staple food either as untreated or pretreated form using hot air drying (Doymaz, 2005; Sobukola, 2009; Doymaz, 2011; Ismail and IbnIdriss, 2013; Honore *et al*., 2014). However, information on the drying of plantain using natural convection is scarce which is what facilitated this research. Hot air is used in many industrial drying applications due to several advantages including fast and uniform drying (Minguez-Mosquera *et al*. 1994; Ayensu, 1997). Some of the staple food manufacturers in Nigeria also use hot air to dry plantain chips by the method of flash drying. However, they find it difficult to control the

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process and also to obtain required quality parameters, specifically the volume expansion. This may be mainly attributed to the lack of reliable information on suitable drying temperature and drying kinetics of plantain during hot air drying. The study and modelling of the drying kinetics take into account the variation with time of heat and moisture transfers. As far as moisture content is concerned, its variation with time defines the drying rate:

$$-\frac{dX}{dt} = -\frac{1}{Ms} * \frac{dM}{dt} \tag{1}$$

In the above relationship, *m* is the mass of the product sample at time *t*; *Ms*= *m* − *mw* is the dry mass; *mw* is the mass of water in the sample.

II. MATERIALS AND METHODS

A. Raw Materials

Fresh plantains (*Musa Paradisiaca*) were purchased from the local mile 3 market of Port Harcourt, Rivers state. The plantain was washed with distilled water and then cut into rectangular pieces of thickness 2mm, 4mm and 5mm, respectively. The plantain slices were then subjected to open sun, and hot air (oven) drying respectively.

B. Drying Equipment

The drying experiments were conducted in a metal tray placed in the open sun and electric hot air dryer (oven) respectively. The hot air dryer used was fabricated and consists essentially of a collector and drying chamber constructed with metal rack.

C. Open Sun Air Drying

Plantain samples of weight 2.5g, 4.4g and 5.1g were spread in different metal tray respectively and then placed in the open sun from 10.00 a.m to 4.00 p.m daily for 6days. The dry bulb temperature and relative humidity of the surrounding environment were taken four times between 12 noon and 4.00 p.m daily. At the end of drying period of each day, the samples were weighed and their values recorded. This was done until approximately 100% (dry weight basis (d.b)) moisture content was obtained for the dried sample.

D. Hot Air Drying

Plantain sample with weight of 2.5g, 4.4g and 5.1g respectively, were spread in metal trays and each placed in an oven dryer. Drying was carried out at combinations of two dry bulb temperatures (50 and 80^{0}C). At 30min interval, samples were withdrawn from the dryer and weighed until approximately 100% (dry weight basis (d.b)) final moisture content was obtained. The moisture content and the moisture loss of both the fresh and dried samples were determined. The drying rate of the samples was calculated based on weight of water removed per unit time and per kilogram of dry matter (solid) and expressed in units of kg^{-1}h^{-1}(Agarry *et al*., 2005, Agarry*et al*., 2006).

E. Mathematical Modelling

Thin-layer mathematical drying models describe the drying phenomenon in a unified way regardless of the controlling mechanisms (Kingsly *et al*., 2007). In thin layer drying, the moisture ratio during drying was calculated according to Eq. (2)

$$MR = \frac{M - Me}{M0 - Me} \tag{2}$$

where MR is the dimensionless moisture ratio, M, the average moisture content at time t, Mo , the initial moisture content, and Me, the equilibrium moisture content respectively, on dry weight basis.

During thin layer drying of plantain chips in open sun and electric oven dryer, the samples was not exposed to uniform relative humidity and temperature continuously. As a result of this, the equilibrium moisture content was not determined and since this was usually not high for food materials (Togrul and Pehlivan, 2004; Waewsak *et al*., 2006), the equilibrium moisture content was assumed to be zero. Thus, the moisture ratio (Eq.2) was then simplified according to Pala *et al*., (1996) and Kingsly *et al*., (2007) to:

$$MR = \frac{M}{Mo} \tag{3}$$

The recorded moisture loss for each sample were thenused to plot the drying curves. Three known semi-empirical mathematical drying models that expresses relationship between MR and the drying time, t as presented in Table (1) was applied to the drying curves obtained for each sample at each process variables using the non-linear regression analysis to select the best model (based on the quality of fit) that describes the drying characteristics or behavior. Some of these models were recently used for determination of moisture ratio with drying time by Khawas *et al*., (2014).

The regression analysis was performed using MATLAB computer software package (version 6.5). The correlation coefficient (R2) and root mean square error (RMSE) was seen as the major criteria for selection of the best model equation to describe the drying curve. For quality fit, R2 value should be high and RMSE should be low (Demir *et al*., 2004; Erenturk *et al*., 2004). In order to evaluate the goodness of fit of the simulation provided by the proposed (best selected) model, different statistical parameters are usually used. In this study, the mean relative error and root mean square error (Nguyen *et al*., 2004; Simal *et al*., 2005) was calculated as:

$$X^2 = \frac{\sum_{i=1}^{N}\left(MRpre,i - MRexp,i\right)^2}{N - Z} \tag{4}$$

$$RMSE = \left[\frac{\sum_{i=1}^{N}\left(MRpre,i - MRexp,i\right)^2}{N - Z}\right]^{0.5} \tag{5}$$

where MRexp,i and MRpred,i are the ith experimental and predicted moisture ratio, respectively, N is the number of observations and z is the number of parameters. In this study, the nonlinear or linear regression analysis was adopted using Matlab.

TABLE 1. Mathematical models given by various authors for the drying curves.

Model Name	Model	Reference
Lewis	$MR = \exp(-kt)$	Doymaz and Ismail(2011)
Modified Page	$MR = \exp((-kt)^n)$	Arslan and Ozcan (2010a,b)
Page	$MR = \exp(-kt^n)$	Jangam*et al*., (2008)

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where k is the drying constant and a, b, n are empirical constants.

F. Effective Moisture Diffusivity

Fick's second equation of diffusion is used to calculate the effective diffusivity, considering a constant moisture diffusivity, infinite slab geometry and uniform initial moisture distribution:

$$MR = \frac{8}{\pi^2}\sum_{i=1}^{\infty}\frac{1}{(2n+1)^2}\exp\left(\frac{-(2n+1)^2\pi^2}{4L^2}D_{eff}*t\right) \quad (6)$$

Where D_{eff} is the effective diffusivity (m2/s) and L is the thickness(Here half) of layer (m). Eq. (6) can be simplified by taking the first term which gives:

$$MR = \frac{8}{\pi^2}\exp\left(-\frac{\pi^2 Deff*t}{4L^2}\right) \quad (7)$$

Eq. (7) is evaluated numerically for Fourier number, F_0 = Deff · t/4L2, for diffusion and can be rewritten as Eq. (8) (Sharma& Prasad, 2004; Sharma *et al.*, 2005):

$$MR = \frac{8}{\pi^2}\exp(-\pi^2 F_0) \quad (8)$$

Thus:

$$F_0 = -0.101In(MR) - 0.0213 \quad (9)$$

The effective moisture diffusivity was calculated using Eq. (10) as:

$$Deff = \frac{F_0}{\left(\frac{t}{4L^2}\right)} \quad (10)$$

III. Results and Discussion

The results of the experiment are presented in Table 1-2 and 3-4 for forced and free convectional drying of plantain chips respectively. Drying curves of drying rate over drying period were constructed to depict drying profile graphically. The plot of drying curve is presented in Figures 1 and 2 which shows that the moisture loss of plantain chips increases with an increase in temperature for both weights of the chips. It also showed that the drying of 2cm, of weight 2.5g of plantain proceeded more rapidly at higher air temperatures than the 4cm and 5cm weight (4.4 and 5.1) g of plantain chips respectively.

TABLE 1. Moisture loss, drying rate, and moisture ratio for 2cm sample of plantain under free convection

Time (days)	Thickness (mm)	Ml	Dr	Mr
0	2.5000	0.0000	0.0000	1.0000
1	2.2000	0.1200	0.0600	0.8800
2	1.8000	0.2800	0.0700	0.7200
3	1.8000	0.2800	0.0467	0.7200
4	1.8000	0.2800	0.0350	0.7200
5	1.5000	0.4000	0.0400	0.6000
6	1.4000	0.4400	0.0367	0.5600

where Ml, Dr, Mr are Moisture loss, Drying rate and Moisture ratio of sample respectively

TABLE 2. Moisture loss, drying rate, and moisture ratio for 4cm sample of plantain under free convection.

Time (days)	Thickness (mm)	Ml	Dr	Mr
0	4.4000	0.0000	0.0000	1.0000
1	4.1000	0.0682	0.0600	0.9318
2	3.6000	0.1818	0.0800	0.8182
3	3.6000	0.1818	0.0533	0.8182
4	3.3000	0.2500	0.0550	0.7500
5	3.0000	0.3182	0.0560	0.6818
6	3.0000	0.3182	0.0467	0.6818

TABLE 3. Moisture loss, drying rate, and moisture ratio for 5cm sample of plantain under free convection.

Time (days)	Thickness (mm)	Ml	Dr	Mr
0	5.1000	0.0000	0.0000	1.0000
1	4.9000	0.0392	0.0400	0.9608
2	4.4000	0.1373	0.0700	0.8627
3	4.4000	0.1373	0.0467	0.8627
4	1.000	0.1961	0.0500	0.8039
5	4.0000	0.2157	0.0440	0.7843
6	4.0000	0.2157	0.0367	0.7843

TABLE 4. Moisture loss, drying rate, and moisture ratio for 2cm sample of plantain under forced convection.

Time (days)	Thickness (mm)	Ml	Dr	Mr
0	2.5000	0.0000	0.0000	1.0000
30	2.2000	0.1200	0.1500	0.8800
60	1.8000	0.2800	0.1750	0.7200
90	1.7000	0.3200	0.1333	0.6800
120	1.6000	0.3600	0.1125	0.6400
150	1.4000	0.4400	0.1100	0.5600
180	1.3900	0.4440	0.0925	0.5560

TABLE 5. Moisture loss, drying rate, and moisture ratio for 4cm sample of plantain under forced convection.

Time (days)	Thickness (mm)	Ml	Dr	Mr
0	4.4000	0.0000	0.0000	1.0000
30	4.1000	0.0682	0.1500	0.9318
60	3.6000	0.1818	0.2000	0.8182
90	3.3000	0.2500	0.1833	0.7500
120	3.0000	0.3182	0.1750	0.6818
150	2.9000	0.3409	0.1500	0.6591
180	2.8900	0.3432	0.1258	0.6568

TABLE 6. Moisture loss, drying rate, and moisture ratio for 5cm sample of plantain under forced convection.

Time (days)	Thickness (mm)	Ml	Dr	Mr
0	5.1000	0.0000	0.0000	1.0000
30	4.9000	0.0392	0.1000	0.9608
60	4.4000	0.1373	0.1750	0.8627
90	4.3000	0.1569	0.1333	0.8431
120	4.2900	0.1588	0.1012	0.8412
150	3.8000	0.2549	0.1300	0.7451
180	3.7900	0.2569	0.1092	0.7431

As the material dries, removal of moisture from the inside became slower thereby requiring more energy to detach water molecules from the solid matrix. The plot also showed that drying time required attaining equilibrium moisture content decreased as the temperature increased. The plot further shows that drying rate was higher at 80^0C than 50^0C and that the entire drying.

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Tables 1-6 above shows the initial weights of the various samples at different time, it was observed that weight of the sample reduces as time increases.

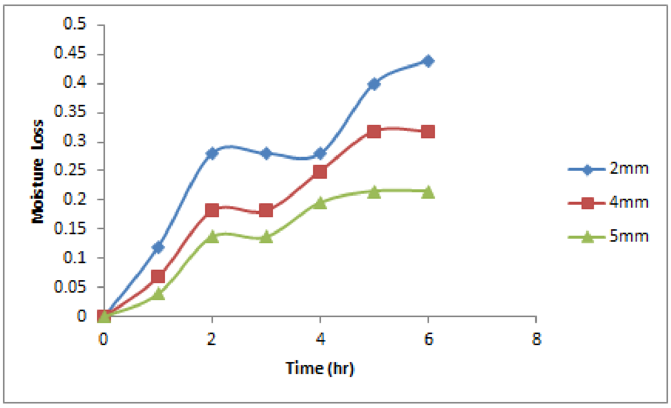

Fig. 1. Variation of moisture content with drying time under free convection.

From Figure 1, it was observed that the weight of the sample reduces as time increases which means that the moisture loss is directly proportional to time, because as time increases, the amount of water being removed from the sample also increases and if this is allowed to continue for a long period, it will come to a point when there will be about 100% moisture lost where the system will attain steady state, at this point, the moisture content will be the same.

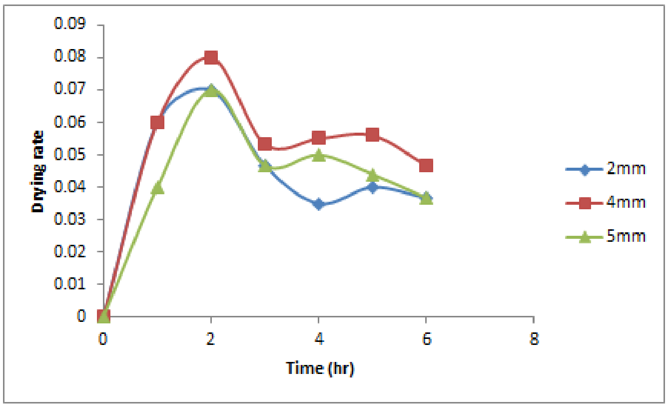

Fig. 2. Variation of drying rate with time under free convection

From Figure 2, it was observed that, initially the drying rate increase with time which is known as the initial period and attained a peak drying time at 2 hours. After 2 hrs the drying rate started decreasing with an increase in time. The decrease in drying rate as time increases is known as the falling rate period. This is because the migration of moisture from the inner interstices of each particle to the outer surface becomes the limiting factor that reduces the drying rate.

Moisture ratio represents the amount of moisture remaining in the plantain chips sample reported to the initial moisture content. From Figure 3, it is seen that as the time increases, the moisture ration decreases; showing that the moisture ratio is inversely proportional to time.

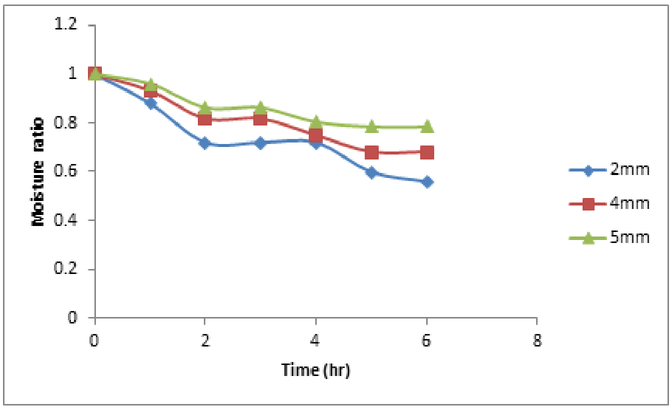

Fig. 3. Variation of moisture ratio with time under free convection.

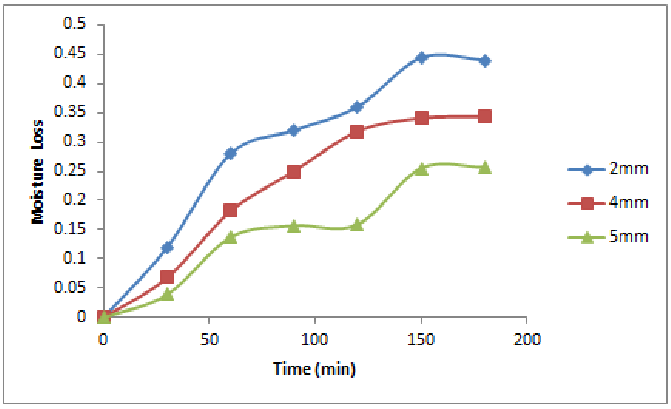

Fig. 4. Variation of Moisture content with time under force convection.

From Figure 4, it was observed that the weight of the sample reduces as time increases which means that the moisture loss is directly proportional to time, because as time increases, the amount of water being removed from the sample also increases at a faster rate and if this is allowed to continue for a long period, it will come to a point when there will be about 100% moisture lost where the system will attain steady state, at this point, the moisture content will be the same.

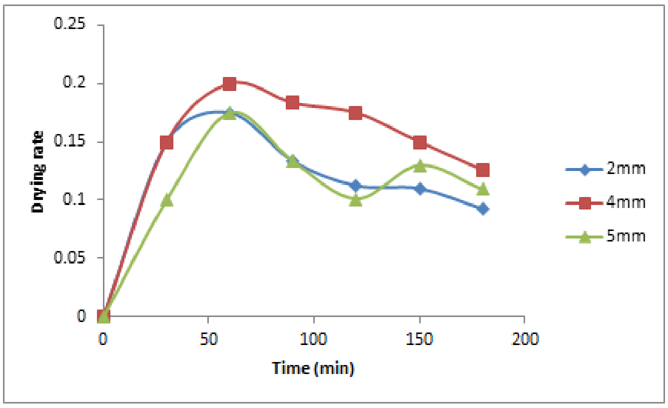

Fig. 5. Variation of drying rate with time under force convection.

From Figure 5, it was observed that, initially the drying rate increase with time which is known as the initial period and later it experienced constancy as time increase which is at constant rate and later the drying rate started decreasing with an increase in time. The decrease in drying rate as time increases is known as the falling rate period. This is because the migration of moisture from the inner interstices of each particle to the outer surface becomes the limiting factor that reduces the drying rate.

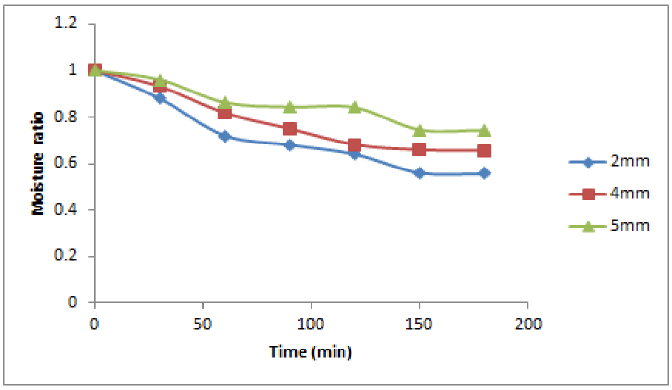

Fig. 6. Variation of moisture ratio with time under force convection.

Moisture ratio represents the amount of moisture remaining in the plantain chips sample reported to the initial moisture content. From Figure 6, it is seen that as the time increases, the moisture ration decreases; showing that the moisture ratio is inversely proportional to time.

Table 7 and 8 shows the summaries of the regression analyses of 5cm thickness of plantain using Lewis, Page and Modified page thin-layer models at 50^{O}C and 80^{o}C respectively. 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 R2009b Matlab.

TABLE 7. Regression analysis of 5cm size of thickness at 50^{o}C.

Model name	**Coefficients**		**Regression parameters**		
	K	N	R^2	RMSE	X^2
Lewis	0.0038		0.9900	0.0236	0.0006
Page	0.0037	1.0059	0.9938	0.0236	0.0006
Modified page	0.0038	1.0059	0.9900	0.0238	0.0006

Table 7 shows the regression analysis of 5cm thickness size of the plantain at 50^{0}C. The model 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 5cm plantain chip 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 7 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.

TABLE 8. Regression analysis of 5cm size of thickness at 80^{o}C.

Model name	**Coefficients**		**Regression parameters**		
	K	N	R^2	RMSE	X^2
Lewis	0.0054		0.9738	0.0399	0.0006
Page	0.0120	0.8461	0.9895	0.0236	0.0006
Modified page	0.0054	0.8461	0.9844	0.0238	0.0006

Table 8 shows the summary of the regression analysis of the 5cm thickness size of plantain at 80^{0}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.

IV. CONCLUSION

From the experiment it was observed that at 50^{o}C, the model 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 5mm 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. Also, at 80^{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.

It may be concluded from the research that Page model best described the drying characteristics of the plantain sample at room Temperature and within 50^{0}C-80^{0}C temperature range under forced and free convection conditions respectively. Therefore, the moisture ratio and consequently the moisture content at any given time within the temperature range may accurately be determined with the Page model. It was also observed that the thickness of the sample significantly affect the drying rate both in free and forced convection.

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