INDIAN JOURNAL OF
ENGINEERING

19(51), 2022

Effective moisture diffusivity determination and mathematical modelling of the drying curves of unripe plantain chips (*Musa paradisiaca*)

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To Cite:
Egbe EW, Ebienfa PDI, David I, Okosemiema MR. Effective moisture diffusivity determination and mathematical modelling of the drying curves of unripe plantain chips (*Musa paradisiaca*). *Indian Journal of Engineering*, 2022, 19(51), 85-99

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Peer-Review History
Received: 23 January 2022
Reviewed & Revised: 24/January/2022 to 06/March/2022
Accepted: 08 March 2022
Published: 10 March 2022

Peer-Review Model
External peer-review was done through double-blind method.

DISCOVERY
SCIENTIFIC SOCIETY

ABSTRACT

Plantains undergo rapid respiration after harvest, making it a short-lived agricultural product that requires urgent attention immediately after harvest. Therefore, plantain has to go through processing to stay longer and that process involves drying. Drying is a method for long-term storage. This study thus, effective moisture diffusivity determination and mathematical modelling of the drying curves of unripe plantain chips of different thicknesses (3cm, 4cm and 5cm) in thin layer using a laboratory convective oven dryer. A temperature range of 60-80^{0}C in multiples of 10^{0}C was selected and applied. Results were fitted to three thin-layer models of Lewis, Henderson and Page, and parameters (R^2, RMSE, X^2) to select the suitable estimating thin-layer model. R^2 values ranging from (0.234 - 0.8954) for Lewis model; (0.234 - 0.8954) for Henderson model; (0.975 - 0.9796) for page model and RMSE values ranged (0.001197 - 0.192845) for Lewis model; (0.007602 - 0.016426) for Henderson model and (0.021557 – 0.047302) for Page model at the drying temperatures applied. The respective X^2 values ranging from (0.000001457-0.039048666) for Lewis model, (0.000007064 – 0.026770973) for Henderson model, (0.000473021 – 0.002032983) for Page model (approximately = 0). Therefore, from the statistical analysis the Lewis model showed a reliable prediction for the drying Characteristics of unripe plantain slices at the chosen temperatures without a constant rate period but observed a falling rate period. The moisture diffusivity effectiveness rises from 3.83×10^{-8} - 8.75×10^{-8} m^2/s, 3.94×10^{-8}- 3.27×10^{-8} m^2/s and 2.26×10^{-8} -5.22×10^{-8} m^2/s for 3mm, 4mm and 5mm slice thickness respectively. Therefore, temperature dependence of moisture diffusivity was found to obey Arrhenius Law.

Keywords: plantain chips; agricultural product; *Musa paradisiaca*

1. INTRODUCTION

Plantain is botanically known as *Musa paradisiaca*, it is a perennial crop belonging to the kingdom of plantain and musaceare family. It is widely harvested in south-south part of Nigeria. Plantain is greenish in nature. Unripe plantain is highly nutritive and medical important agricultural biomaterial cultivated in tropical location and is an essential food material in Nigeria and Sub –Sahara Africa (Eklou et al., 2006; Hahou et al., 2003). After harvested it passes through pre-treated processes by manually pilling off the greenish part of the plant to prepare a delicious meal popularly called kiki-fia (KKF) in Bayelsa state Nigeria and sometimes sliced into chips (size reduction) and then dried or fried. Plantain has had high water systemic, so drying is an application to reduce its moisture content into low moisture content level in order to decrease microbial activities that causes early deterioration in plantain therefore, increasing its shelf life then and then possibly transferred into packaging unit and sale in the market places either in retailer or wholesaler.

Plantains undergo rapid respiration after harvest, making it a short-lived agricultural product that requires urgent attention immediately after harvest. Therefore, plantain has to go through processing to stay longer and that process involves drying. And in other to achieve a good, fast and accurate drying process (Senadeera & Kosse 2021; Yusuf et al., 2021), the oven drying method is preferable**.** Plantain production is available at certain period of the year whereas consumption is throughout the year so there is necessity to reduce the post-harvest deterioration by passing through pre-treatment process with lower moisture content. Plantain has however been having an increasing surplus production since 2001. In 2010, it is expected that there will be a surplus of 633,000Mt and in 2015 about 852,000Mt this means that these surpluses have to be exported, processed or go to waste (Dankye et al., 2007).

Plantain chips are dried or fried and milled into fine particle called plantain flour. Traditionally, the plantain flour is use other purposes dishes like akara, Ukpo, ogede and soup (Onuoha et al., 2014).

In technical literature it is shows that plantain have a lot health benefit because it has low sugar content (Swenner, 1990). The duration of storage of plantain is affected which limited plantain production in Nigeria due to absent of well manufactured storage facilities extended shelf life (Will et al., 1989, Smiles et al., 2005).

Several researchers have investigated the drying characteristic dying curves of most of these food materials using empirical models such as page model (Davies et al., 2020), Henderson and pabis model (Karathonos and Belessiotis, 1999), Logarithmic model (Yaldiz et al., 2001), two term exponential model (Akpinar et al., 2003), Newton model best fitted for Strawberry under solar drying (Beltagy et al., 2007) and Egbe, (2022) examined the influence of temperature on dehydration kinetics of pre-treated and un-treated yam slices, Henderson model showed reliable suitable for predicting the drying kinetic for both treated and untreated yam slice.

The objective of the study is to use oven dry method to convert the raw plantain chips to dried plantain chip for availability throughout the year. Nevertheless, to achieve this objective the unripe plantain was sliced into chips using vanier caliper with thicknesses such as 2mm, 3mm and 4mm with temperature ranged from 60-90°C and to input the experimental values into linearized page, Henderson and Lewis model to characterize the drying process.

2. MATERIALS AND METHOD

Fresh plantains (*Musa paradisciaca*) were purchased from Ondewari local market in southern Ijaw local government area Bayelsa State, Nigeria. The fresh manured plantain was washed with distilled water and with knife manually sliced into chips measured to be 2mm, 3mm and 4mm using a vanier caliper The sliced plantain chips were then subjected to oven dry method (plate 1) with temperature ranging from 60-70°C in a multiple of 10°C. At very 10mins the plantain chips were removed from the oven dryer and weigh using electronic weighing balance (plate 2) until final moisture content was observed.

2.1. Fresh plantains (*Musa paradisciaca*)

Unripe Plantain (*Musa paradisciaca*) as we all know is one of Nigeria's basic foods and West Africa, they are rich in fibre, high in antioxidant and also very good for the heart.

The plantains used in this research work were matured unripe plantains and bought from a nearby market in Ondewari in Bayelsa State, Nigeria.

2.2. Knife

The stainless-steel knife which was also bought from a nearby market in Ondewri, was used to peel and slice the unripe plantain.

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2.3. Vernier Calliper

The Vernier calliper is a tool used to make extremely accurate linear measurements that was invented in 1631 by Pierre Vernier of France. It employs two graduated scales: a primary scale comparable to a ruler and a particularly graduated auxiliary scale, the Vernier, which glides parallel to the main scale and allows readings to a fraction of a division on the main scale. This was used to measure the slice thickness of the plantain.

2.4. Oven

The WTC Binder oven was used for all drying experiments (plate 1).

Plate 1: WTC Binder Oven

2.5. Weighing Balance

A weighing balance is an instrument which was employed to calculate the weight or mass of the plantain. The sliced plantains of different thicknesses were weighted using the laboratory-type digital weighing balance with 0.01-g precision (plate 2).

Plate 2: laboratory–type digital balance with 0.01-g precision

2.6. Thin Layer Drying Models

The drying data from the experiments of unripe plantain obtained during the drying the food processing laboratory at different temperatures will be fitted into three commonly used Thin-Layer drying models and the dimension less moisture ratio of the samples was calculated as:

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

where Mt, Mo and Me are moistures contents at any time of drying (%wb), initial moisture content (%wb) and equilibrium moisture contents (%wb) respectively. The values of M_e are relatively small compared to M_t and M_o for long drying times and accordingly one can write (Evin, 2011; Soysol et al, 2006);

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$$MR = \frac{M_t}{M_o} \quad 2$$

$$\mathrm{MR} = \frac{\mathrm{M} - \mathrm{M_e}}{\mathrm{M_o} - \mathrm{M_e}} = \frac{8}{\pi^2} \int_{n=1}^{\infty} \frac{1}{n^2} e^{-(n)^{2}\frac{\pi^2 D_e t}{L^2}} \quad 3$$

$$\mathrm{MR} = 0.8106 = \int_{n=1}^{\infty} \varepsilon_n{}^{-2}\, e^{-9.87\varepsilon_n(\frac{D_e t}{r_c{}^2})} \quad 4$$

$$\mathrm{MR} = 0.8106 = e^{-9.87(\frac{D_e t}{r_c{}^2})} \quad 5$$

Taking natural log on both sides, equation 5 will linearize to

$$\ln(\mathrm{MR}) = -\left(47\mathrm{De}\left(\frac{1}{R_c}\right)^2 \mathrm{t} + 1\right) \quad 6$$

Moisture Diffusivity Effectiveness

The moisture diffusivity Effectiveness D_e drying parameter can be estimated from the slope of the plot when Equation 6 is plotted on a logarithmic scale (known as the slope method), as follows (Guine et al, 2011)

$$\mathrm{De} = -slope\,\frac{[r_c{}^2]}{47} \quad 7$$

Activation Energy Ea.

The energy necessary to induce molecular diffusion in biomaterials to produce drying is referred to as activation energy. Because temperature, t, is a quantifiable parameter in this work, an Arrhenius type function was utilized to determine the activation energy as (Saxena and Dash, 2015; Da Silva *et al*, 2015)

$$(\mathrm{De} = \mathrm{Do} = \mathrm{e}^{-\mathrm{E_a}/\mathrm{Rt}}) \quad 8$$

where

E_a = activation energy, kJ/mol

D_e = effective diffusivity at t°K, m^2/s.

D_o = pre-exponential factor of the Arrhenius equation at 0°K, m^2/s.

R = universal gas constant (8.314×10^{-3}, kJ/mol.K).

t = air temperature expressed in °K

Simplification of Equation 8 gives

$$\ln\mathrm{De} = \ln\mathrm{Do} -= \frac{\mathrm{E_a}}{\mathrm{R}}\mathrm{t}^{-1} \quad 9$$

or $$-\frac{\mathrm{E_a}}{\mathrm{R}}\mathrm{t}^{-1} = \ln D_e - \ln D_o \quad 10$$

$$\frac{\mathrm{E_a}}{\mathrm{Rt}} = \ln\left(\frac{D_o}{D_e}\right) \quad 11$$

$$\frac{\mathrm{E_a}}{\mathrm{R}}\mathrm{t}^{-1} = \ln\left(\frac{D_o}{D_e}\right) \quad 12$$

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Plotting of $\ln D_e$ as a function of t^{-1} with regression line of slope, z as;

$$z = -\frac{E_a}{R} \text{ (as in Equation 12)} \qquad 13$$

When, the activation energy can be estimated as (Taheri-Garavanda et al, 2011; Navneet et al, 2012).

$$E_a = -zR \qquad 14$$

Table 1: Selected Thin-layer Models

Model Name	Model	References
Lewis	MR =exp(-kt)	Doymaz and Ismail (2011)
Page	MR =exp(-kt^n)	Jangan et al, (2008)
Henderson and pabis	MR = aexp(-kt)	Figiel (2010)

Where; k is the drying constant and a, n are equation constant

2.7. Statistical Analysis

The ability of the tested mathematical model to represent the experimental data was evaluated through the coefficient of determination (R^2), the reduced chi-square (X^2) and the root mean square error (MSE) parameters. The criteria is that, the higher the R^2 and lower the (MSE) and X^2 values, the better the fitting (Egbe, 2022, Wang et al, 2007: Ozbek & Dadah, 2007,). The aforementioned parameters are mathematically defined as follows;

$$R^2 = 1\left[\sum_{i=1}^{n}(MR_{pre,i} - MR_{exp,i})^2\right] \qquad (15)$$

$$RMSE = \sqrt{\frac{\sum_i^n (MR_{pre} - MR_{exp})^2}{N}} \qquad (16)$$

$$X^2 = \sum_{i=1}^{n} \frac{(MR_{pre} - MR_{exp})^2}{N-K} \qquad (17)$$

where;

exp = experimental data

pre = predicted data

N = number of observations

K = number of constants.

3. RESULTS AND DISSCUSIONS

3.1. Results

It was necessary to transform drying results gained from experiment into different models to know the best model to use when designing a machine to dry unripe plantain samples. Fig.1 to 6 presents changes in moisture ratio with drying time of the unripe plantain. As with literature report on drying of unripe plantain samples, the drying environment had moisture movement is significantly influenced on the unripe plantain samples in drying as expected (Zibokere and Egbe, 2020, Burubai, 2015; Ikrang, 2014; Davies et al 2012; Jain and Pathare, 2007). The figure shows that on the same state of drying indicated by the moisture ratio, drying time increase greatly with drying temperature.

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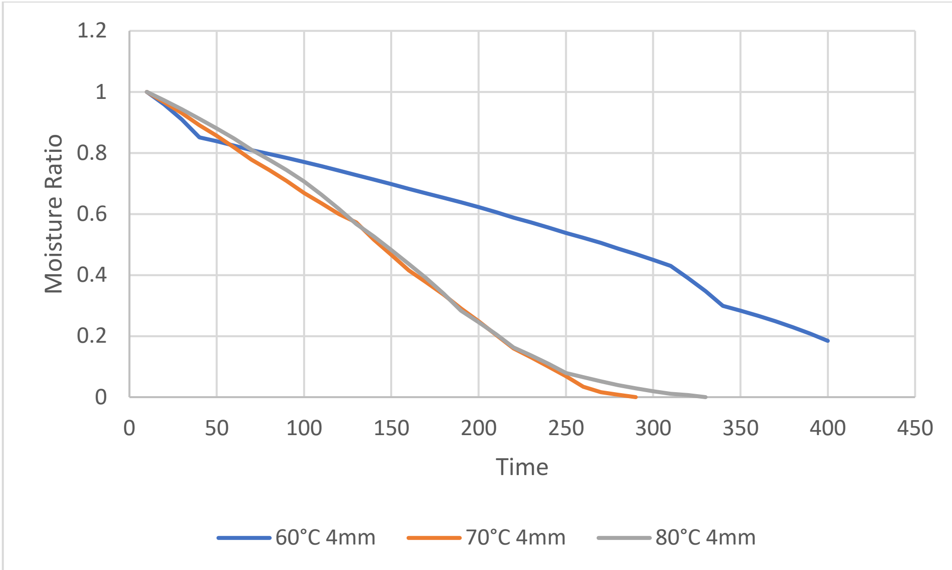

Fig.1: Moisture ratio versus time of specimen at different temperatures with 4mm thickness

The drying curves in Fig. 2 depict the general trend of characteristic drying curves as reported for many bio- materials. The curves present initial steeper slope and become asymptotic to the axis of drying time even with changing drying temperatures. This form adequately describes a more rapid initial moisture loss, and as moisture available for evaporation at the specimen's surface become lesser in drying (kilic, 2009; Zibokere and Egbe 2019; Sankat and Mujaffar 2006).

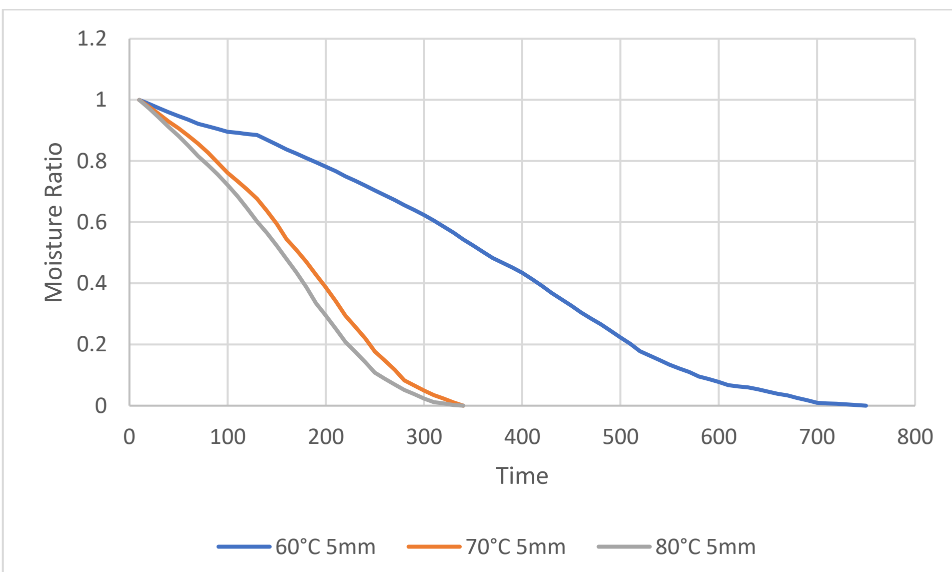

Fig. 2: Moisture ratio versus time of the specimen at different temperatures with 5mm thickness

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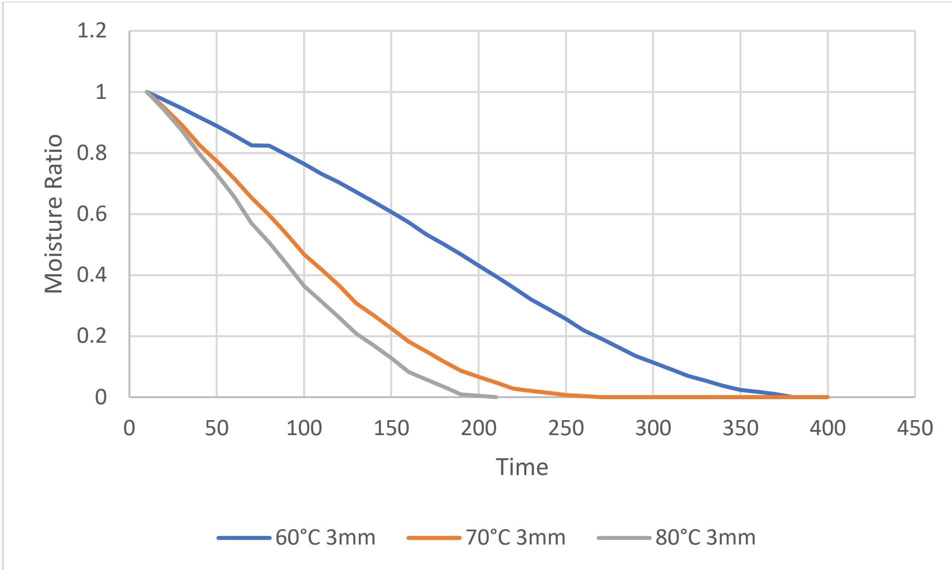

Fig. 3: Moisture ratio versus time of the specimen at different temperatures with 3mm thickness

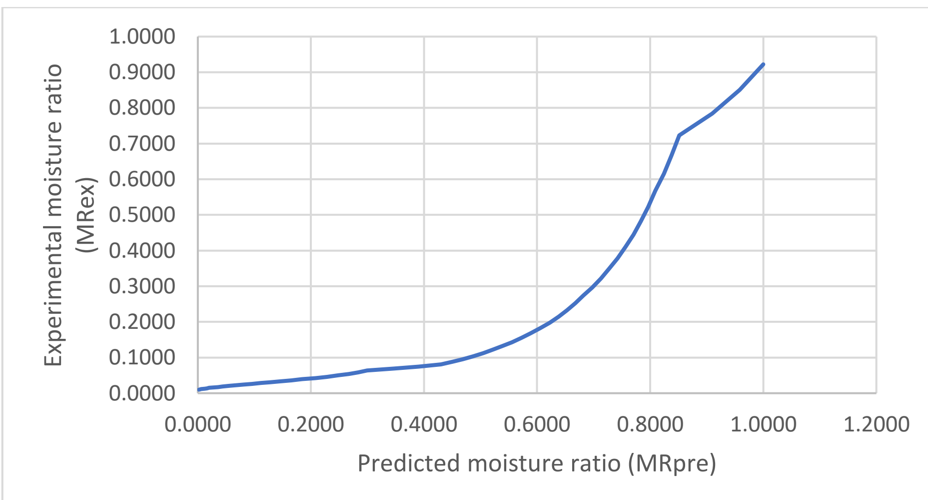

Fig. 4: Experimental moisture ratio versus Predicted moisture ratio of Unripe Plantain for Lewis model at 60°C

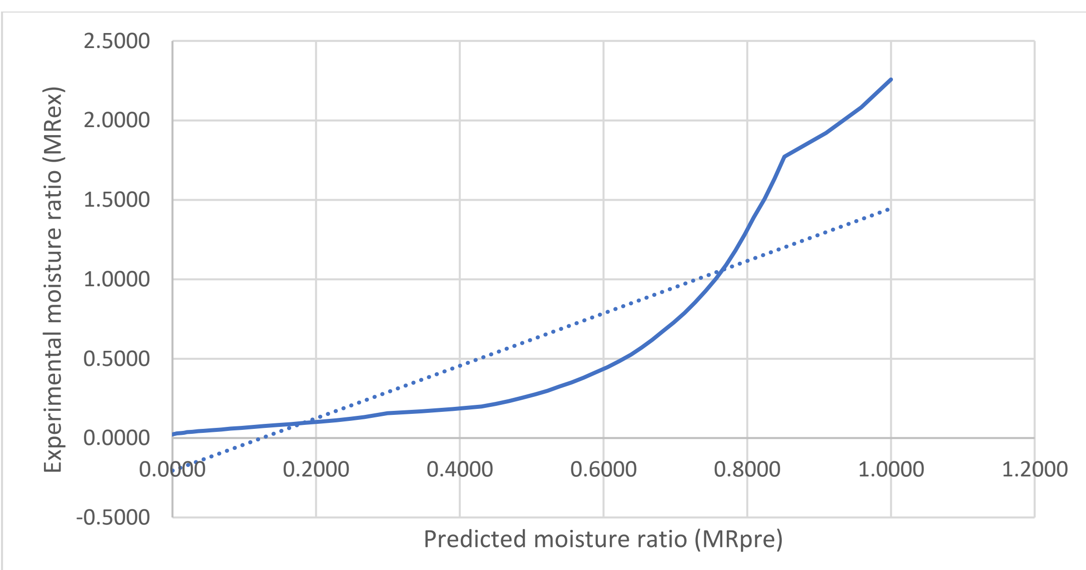

Fig. 5: Experimental moisture ratio versus Predicted moisture ratio of Unripe Plantain for Henderson model at 60°C

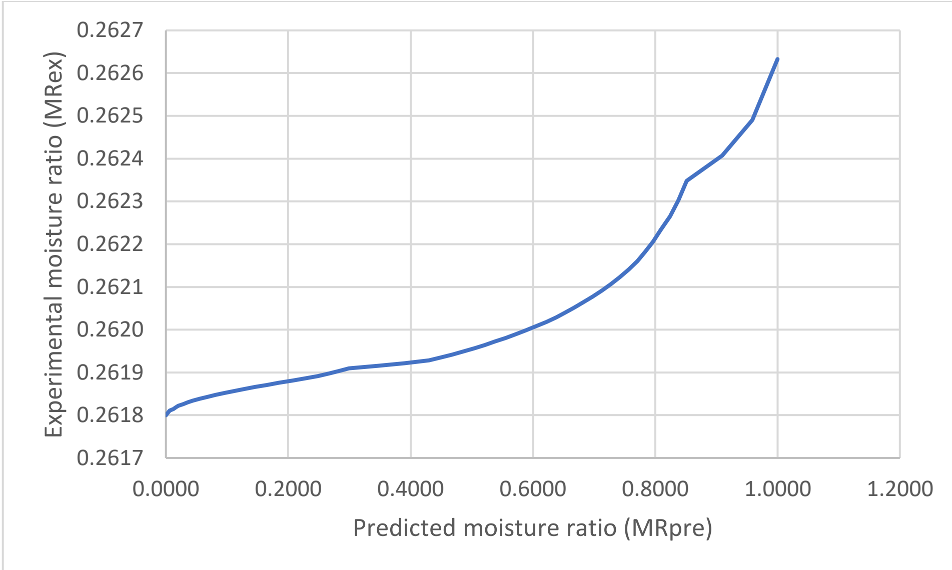

Fig.6: Experimental moisture ratio versus Predicted moisture ratio of Unripe Plantain for Page model at 60°C

3.2. Fitting Experimental Data into Thin Layer Drying Model

Table 1 summarizes the statistical result from the thin-layer drying models for the different drying temperature selected in this work. The model with the highest R^2 value, and the least X^2 and RMSE values was the criteria applied in selecting the best model describing the drying properties of unripe plantain in thin layers. The fitting statistical results in the table 2 to 3 showed that the R^2 values were consistently high throughout all models, all scoring respectively above 0.70 except for Page Model that is seen to score above this figure. The sample indicates the suitability of these empirical models in describing drying behaviour of unripe plantain. However, when further turned alongside the other statistical parameters, the model expression of Lewis followed by that of Henderson gave the highest R^2 values and the lowest X^2 and RMSE values within the work's temperature range. It was observed that though the Henderson Model may describe the drying curve for the practical results and conditions for the unripe plantain of this work, it hardly gave a clear and accurate overall view of the important processes involved during drying. Fig.4 to fig. 6 compared experimental data with data predicted with the Lewis, Henderson and Page model at the chosen drying temperatures. Further indicated the suitability of Page Model in describing drying characteristics of unripe plantain samples, similar in trend as observed by Davies et al (2012) for shrimp, Zibokere and Egbe (2021) for fresh water clawed lobster.

Table 2. Statistical parameters of unripe plantain on three selected Thin-layer Drying Model

MODEL	TEMPERATURE (°C)	THICKNESS	R^2	RMSE	X^2
LEWIS MODEL	60	3mm	0.8412	0.036416	0.001326123
	60	4mm	0.7839	0.001197	0.000001457
	60	5mm	0.7932	0.029937	0.000908358
	70	3mm	0.8954	0.036169	0.001358498
	70	4mm	0.7883	0.044211	0.002024376
	70	5mm	0.8272	0.042191	0.001834053
	80	3mm	0.4789	0.192845	0.039048666
	80	4mm	0.234	0.083273	0.007151069
	80	5mm	0.8146	0.042872	0.001893693
HANDERSON MODEL	60	3mm	0.8412	0.007602	0.000059401
	60	4mm	0.7839	0.008333	0.000007064
	60	5mm	0.7932	0.008685	

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	70	3mm	0.8954	0.01485	0.000229338
	70	4mm	0.7883	0.009027	0.000084495
	70	5mm	0.8272	0.007664	0.000060577
	80	3mm	0.8404	0.016426	0.000284801
	80	4mm	0.234	0.016104	0.026770973
	80	5mm	0.8146	0.014801	0.000225906
PAGE MODEL	60	3mm	0.9558	0.037214	0.001384892
	60	4mm	0.9015	0.021557	0.000473021
	60	5mm	0.9298	0.028147	0.000803096
	70	3mm	0.9796	0.025393	0.000670591
	70	4mm	0.9519	0.044276	0.002032983
	70	5mm	0.9555	0.047302	0.00230742
	80	3mm	0.975	0.036429	0.001396914
	80	4mm	0.9662	0.038568	0.001535441
	80	5mm	0.9542	0.039103	0.001576834

Table 3. Statistical parameters of unripe plantain on three selected Thin-layer Drying Model

MODEL	TEMPERATURE (°C)	THICKNESS	K	A	N
LEWIS MODEL	60	3mm	0.0105		
	60	4mm	0.0081		
	60	5mm	0.0062		
	70	3mm	0.0201		
	70	4mm	0.0138		
	70	5mm	0.0115		
	80	3mm	0.0012		
	80	4mm	0.0006		
	80	5mm	0.0147		
HANDERSON MODEL	60	3mm	0.0105	2.1604	
	60	4mm	0.0081	0.8952	
	60	5mm	0.0062	0.9632	
	70	3mm	0.0201	0.9667	
	70	4mm	0.0138	0.8107	
	70	5mm	0.0115	0.8004	
	80	3mm	0.024	0.9682	
	80	4mm	0.0006	0.1379	
	80	5mm	0.0147	1.0353	
PAGE MODEL	60	3mm	1.4465		0.000523
	60	4mm	1.3352		0.000585
	60	5mm	1.4967		0.000141
	70	3mm	1.4598		0.001251
	70	4mm	1.4535		0.000734
	70	5mm	1.5545		0.00032

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	80	3mm	1.483		0.001462
	80	4mm	1.568		0.000404
	80	5mm	1.5584		0.000397

3.3. Determination of Effective moisture (De)

The experimental data obtain from In(MR) against time and the slice thickness as shown in figt.7-10 was used estimated the moisture diffusivity effectiveness during the falling rate period as shown in the table 4. The effective moisture diffusivity tends to increase when the temperature rises. Experimental show the moisture diffusivity effectiveness rises from 3.83×10^{-8} - 8.75×10^{-8} m^2/s, 3.94×10^{-8}- 3.27×10^{-8} m^2/s and 2.26×10^{-8} -5.22×10^{-8} m^2/s for 3mm, 4mm and 5mm slice thickness respectively.

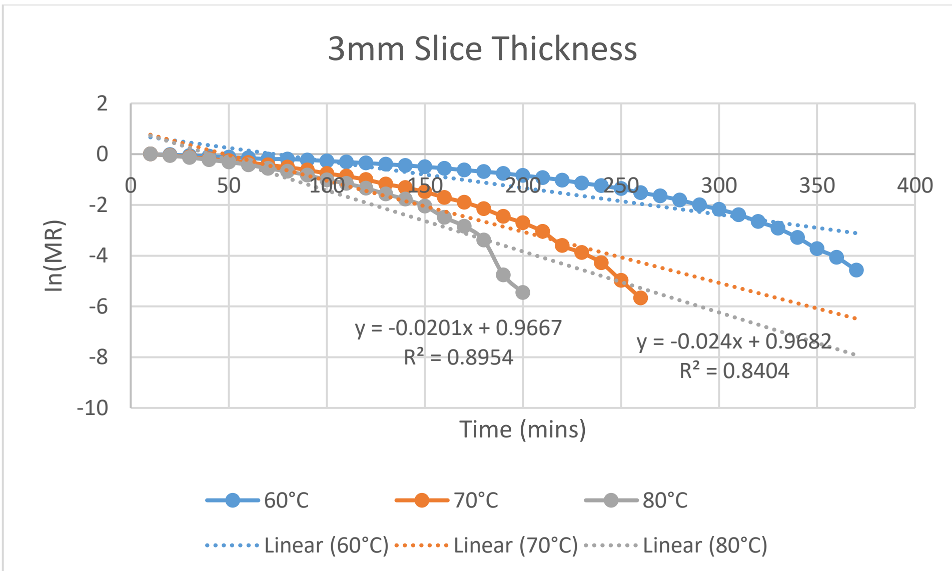

Fig. 7 Drying curve of the specimen at 3mm slice thickness
(Logarithmic moisture ratio vs drying time)

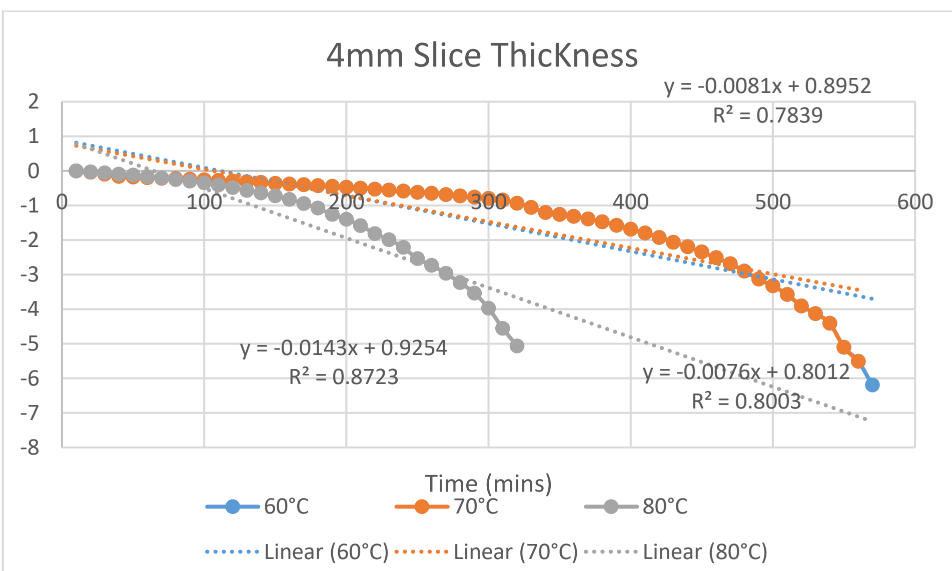

Fig 8. Drying curve of Unripe Plantain (*musa paradisiaca*) at mm slice thickness
(Logarithmic moisture ratio vs drying time)

From fig. 7 regression equations from a linearized equation were developed from a graph In(MR) against time (mins) as shown in equations below 18 to 20

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60°C, y = -0.0105x + 0.7703 R^2 = 0.8412. (18)

70°C, y = -0.0201x + 0.9667 R^2 = 0.8954 (19)

80°C, y = -0.024x + 0.9684 R^2 = 0.8404 (20)

From fig. 8 regression equations from a linearized plot were developed from a graph In(MR) against time (mins) as shown in equations below 21 to 23

60°C, y = -0.008x + 0.8952 R^2 = 0.7839 (21)

70°C, y = -0.076x + 0.8012 R^2 = 0.8003 (22)

80°C, y = -0.0143x + 0.9254 R^2 = 0.8723 (23)

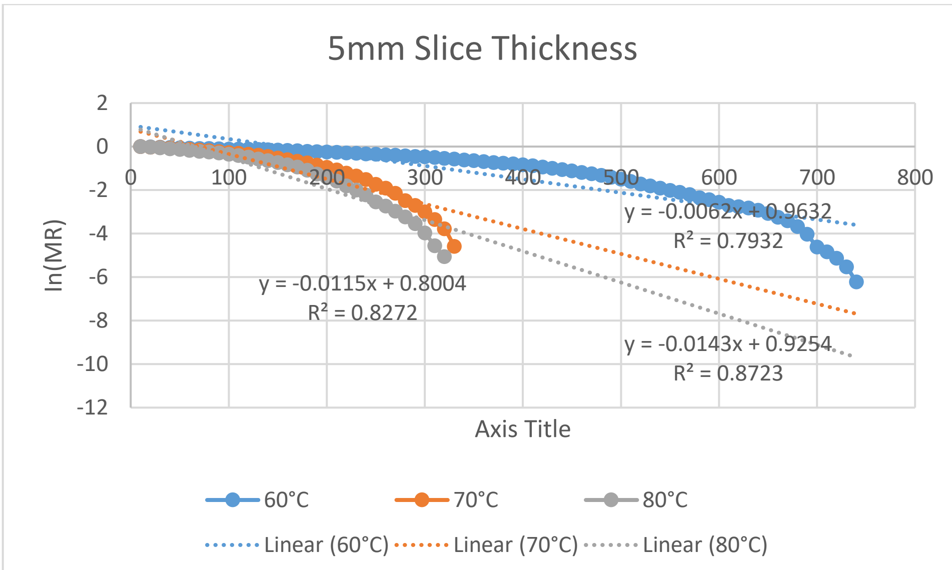

Fig. 9. Drying curve of Unripe Plantain (*musa paradisiaca*) at 5mm slice thickness (Logarithmic moisture ratio vs drying time)

From fig. 9 regression equations from a linearized plot were developed from a graph In(MR) against time (mins) as shown in equations below 24 to 26

60°C, y = -0.006x + 0.9632 R^2 = 0.7932 (24)

70°C , y = -0.0115x + 0.8004 R^2 = 0.8272 (25)

80°C , y = -0.0143x + 0.9254 R^2 = 0.8723 (26)

Table 4. Moisture Diffusivity Effectiveness values of Unripe Plantain (*Musa paradisiaca*)

Temp °C	Slice Thickness (mm)	Average Effective Moisture Diffusivity (m^2/s)
60	3	3.83×10^{-8}
70	3	7.33×10^{-8}
80	3	8.75×10^{-8}
60	4	3.94×10^{-6}
70	4	3.94×10^{-6}
80	4	9.27×10^{-8}
60	5	2.26×10^{-8}
70	5	4.19×10^{-8}
80	5	5.22×10^{-8}

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3.4. Activation Energy, (Ea) for Ripe Plantain *(musa paradisiaca)*

The energy that initiates mass transfer from a wet biomaterial during drying is known as activation energy. Activation energy computed from the InDeff Versus temperature curve, as illustrated in Figure10 to 12, and the influence of temperature of moisture diffusivity was found to obey Arrhenius Law. Activation energy observed in Unripe Plantain *(musa paradisiaca)* were found to increase with an increase with temperature. Ea was discovered to be 10.20, 13.22 and 17.43KJ/mol as the slice thickness grew from 2mm, 3mm and 4mm respectively.

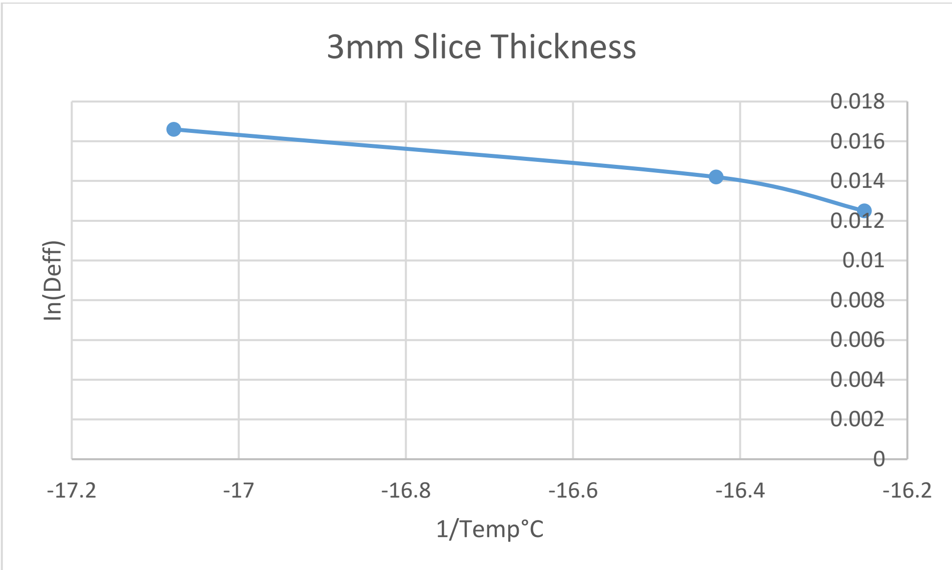

Fig. 10: Estimation of Activation Energy for specimens at 3mm slice thickness

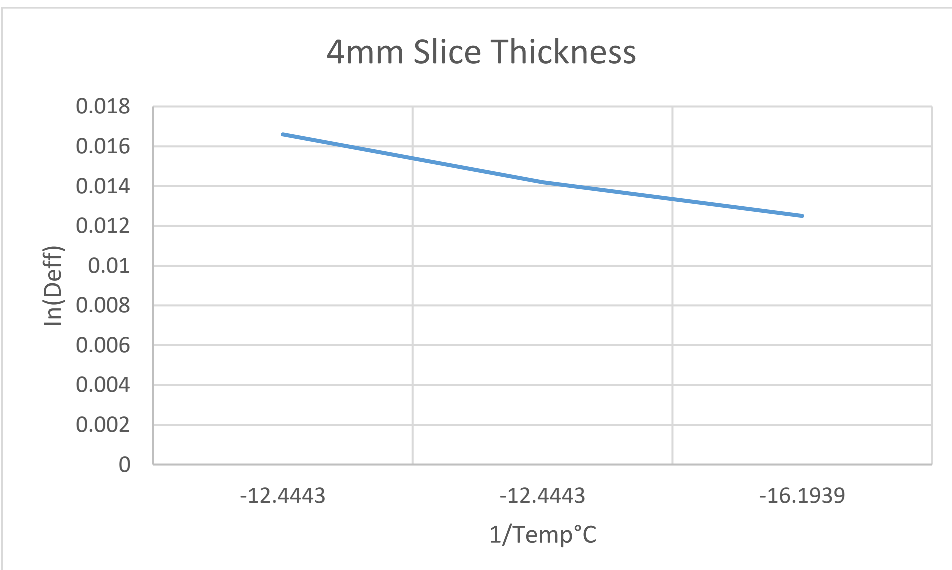

Fig. 11: Estimation of Activation Energy for specimens at 4mm slice thickness

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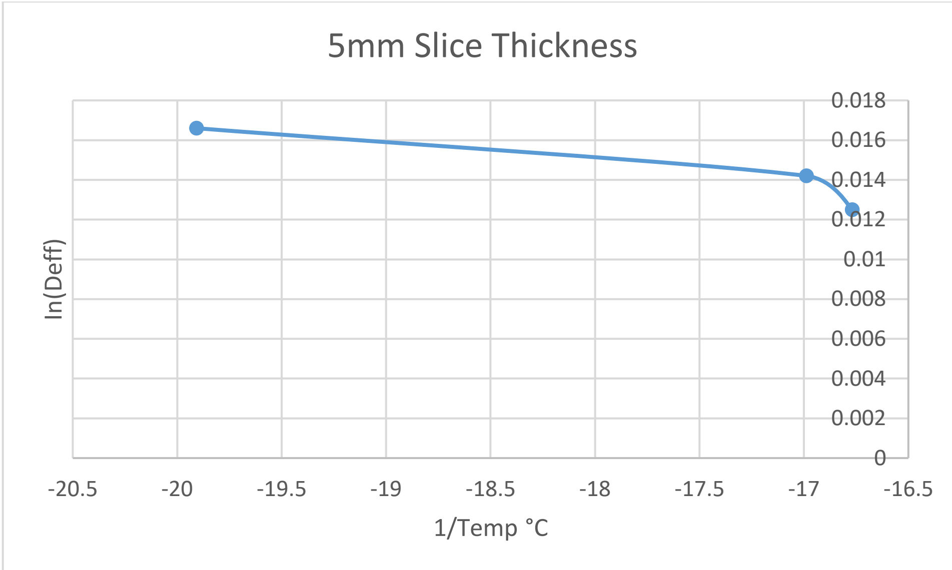

Fig. 12: Estimation of Activation Energy for specimens at 5mm slice thickness

Table 5. Effect of Slice thickness and Activation Energy

Slice Thicknesses(mm)	Activation Energy (KJ/mol)
3	10.20
4	13.22
5	17.43

4. CONCLUSION AND RECOMMENDATION

A research was carried out to ascertain the drying behaviour of unripe plantain (*musa paradisiaca*) on thin layers. Three thin layer models were chosen to suit the experimental results and to explore the best for predicting the drying behaviour of the specimen. The Vernier calliper was then used to measure the thicknesses (3mm, 4mm and 5mm) of the unripe plantain. The drying experiment was carried out using the oven dry technique with temperature ranged from 60 to 80°C. The ability of the mathematical model to represent the experimental result was evaluated through the (R^2, X^2 and MSE) parameters, the criteria is that, the higher the R^2 and lower the (RMSE) and X^2 values, the better the fitting. From the statistical analysis the Lewis model followed by Henderson model shows a reliable prediction for the drying Characteristics of the sample at the chosen temperatures. The drying procedure was discovered to be effective, predominantly in the falling rate period without constant rate period line with several literature reports on other biological materials.

This work has the potential to be valuable in the design process and development of drying equipment for the preservation of Unripe Plantain. The work however limited the selection of thin-layer drying models to only three. An attempt could be made to extend the selection base beyond the limit applied in this work to obtain higher degree of freedom on the statistical exactness using the drying data in order to enhance the design of the drying system.

Funding

This study has not received any external funding.

Conflict of Interest

The author declares that there are no conflicts of interests.

Data and materials availability

All data associated with this study are present in the paper.

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