THIN-LAYER DRYING CHARACTERISTICS AND MODELLING OF RIPE PLANTAIN SLICES *(MUSA PARDISACA)*

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Abstract

Vegetable drying is the most effective method for preserving agricultural products, it is an energy-intensive process. This study thus, thin-layer drying characteristics and modelling of ripe plantain *(musa paradisaca)* was investigated with different slice thicknesses (3mm, 4mm and 5mm) in thin layer using a laboratory convective oven dryer multiples of 10°C in the temperature range of 60 to 80°C was used. A suitable estimating thin-layer model was chosen by fitting the results to the three thin-layer models of Lewis, Henderson, and Page using the parameters (R^2, RMSE, and X^2). It was observed that Henderson model R^2 ranged from 0.9064-0.996, RMSE ranged from 0.021838-0.000346 and X^2 ranged from 0.0017765712-0.0000000447730. Slice thickness tends to increase with activation energy and temperature tends to increase with an increase in effective moisture diffusivity. As a result, the statistical analysis revealed that the Henderson model provided a trustworthy prediction for the drying characteristics of ripe plantain slices at the selected temperatures without a constant rate period but rather a falling rate period.

Keywords: ripe plantain, thin-layer models, slice thickness, drying curves, drying rate, moisture ratio

Introduction

Plantain (*Musa paradisaca*) is one of the most important delicious food consumed in Nigeria. Plantain belongs to the family of plants called Musaceae. Musa paradisiaca is a perennial and herbaceous plant belonging to the family of Musaceae and the genus Musa (Nweze *et al.,* 2015). It is associated with high carbohydrate for millions of African populates. According to published research, it has a low protein and fat content but is very rich in starch and minerals (Swenner, 1990). According to FAO (2006), Nigeria is one of the largest plantain producing countries in the world, she produced 2.103 million tons of harvested plantain fruits as of the year 2014 from 389,000 ha. The overall production has doubled in the last ten years. Poor handling and postharvest diseases of plantain have been described as the causes of high postharvest losses of plantain in the country (Bayeri & Nwachukwu, 2004). Storage environmental conditions, for instance air composition, relative humidity and temperature have significant effect on the shelf-life of plantain. Insufficient storages systems, distribution and lack of ripening techniques contributed to huge losses of plantain fruit in Nigeria (Gajanana *et al.,* 2003).

The nutritional composition of plantain comprises of 35% carbohydrate, 1.2% protein, 0.8% ash and 0.2 to 0.5% fat (Ekpete *et al.,* 2016; Campuzano *et al.,* 2018). Plantain is recognized as one of the major staple foods in Nigeria (Ajayi, 2018). Plantain has medicinal values for the treatment of sore throat, vomiting and tonsillitis diarrhea. According to Asogwa *et al.,* (2021) diabetic patients eat unripe plantains. They are consumed in Nigeria, particularly in the southern region, when ripe, boiled, fried, or roasted, and the pulp is used to make wine. Researchers have observed that plantains have a low glycemic response when consumed, making them a good food for diabetic patients (Eleazu et al., 2010).

Although plantain pulp has been found to be low in protein, it is nutritionally rich in iron, potassium, vitamin A, and ascorbic acid (Ketiku 1973). Unripe plantain locally processed into fufu in Nigeria and other West Africa countries (Ukhum & Ukpebor 1991). On the other hand, it is gradually being used in the preparation of composite flour and weaning foods (Oloaye *et al.,* 2006, Ogazi, 1996). Ogazi, (1982) reported that 80% of plantain is harvesting during the period of September and February and develop a lot of loss or wastage because of lack of storage facilities.

Ripening of plantain occurs when it matures. According to Awan and Ndubuizu (1979) ripening causes changes in the nutritional composition and frictional properties of plantain fruit, which affect the fruit color and texture. Moisture, sugar, protein, lipid and fibre contents of unripe plantain increases during ripening but decrease in carbohydrate as reported by (Kassion, 1986) and (Ogazi, 1986)

It is typically eaten with red palm oil after boiling, or it is pounded and eaten with vegetable stew and meat, and occasionally it is sliced and fried into doodoo (in Yoruba language). However, convectional over heating has low energy efficiency with negative quality effects (Huang, 2013).

Drying is a complicated process that involves both heat and mass transfer. High systemic moisture activity is transferred from the inside to the outside of the food through the process of diffusion, and this is an application that involves removing or reducing moisture activity to a safe level in order to preserve its chemical and physical characteristics (Ruiz and Montero, 2005).

This study thus investigated the effects of temperature and slice thickness on the moisture diffusivity effectiveness and activation energy on dehydration kinetics of ripe plantain (*musa paradisaca*) using an oven dry method with temperature ranging from 60-80°C. Therefore, the objectives of this research are to examine the drying kinetics of ripe plantain using a laboratory convective oven heating and to validate the experimental data obtained by fitting it to three mathematical models that predict thin-layer drying.

2.0 MATERIALS AND METHOD

2.1 Introduction

Three thin- layer models of Lewis, Henderson and Page were used in determining the main objectives of the study. The method of investigation requires the experimental and theoretical approach to arrive at its findings. Experimentally, the results were derived by direct observation of test samples in the laboratory. Theoretically, models were used to determine the thin layer drying characteristics of ripe plantain slices.

2.2 Materials

The following are the materials used in the experimental procedure

2.2.1 Plantain

Ripe plantains are high in fiber, antioxidants, and are also very beneficial for the heart. Plantains that were matured and ripe were purchased at the local market in Ondewari Town, Bayelsa State, Nigeria, for use in this study.

2.2.2. Knife

The ripe plantain was manually peeled and cut into slices using the stainless-steel knife, which was purchased at the neighbourhood market in Ondewari town.

2.2.3 Vernier Calliper

The Vernier calliper is a device for taking extremely accurate linear measurements. It uses two graduated scales: the Vernier, a specially graduated auxiliary scale that slides parallel to the main scale and enables readings to be made down to a fraction of a division on the main scale, and a main scale that resembles a ruler. This was used to gauge the ripe plantain thicknesses (3mm, 4mm, and 5mm) as shown in the Plate 1 below.

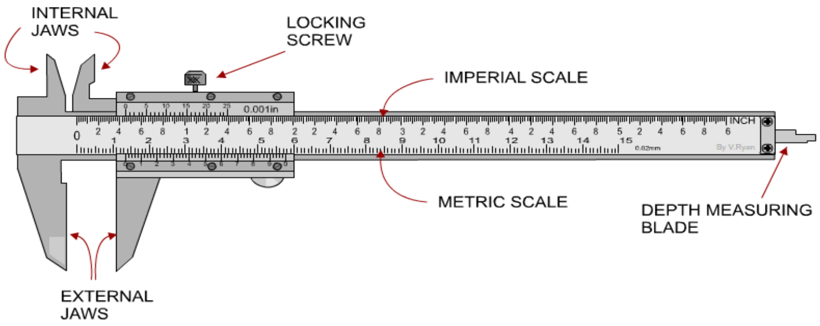

Plate 1: Vernier Calliper

2.2.4 Oven

The WTC Binder oven was used for all drying experiments.

Plate 2: WTC Binder Oven

2.2.5 Weighing Balance

In order to calculate an object weight or mass, a weighing balance is used. With a precision of 0.01 g, the digital laboratory weighing balance was used to weigh the sliced plantains at various thicknesses. Plate 3

Plate 3: laboratory–type digital balance with 0.01-g precision

2.3. Methods:

The ripe plantain for the experiment was bought from Ondewari market Sothern Ijaw Local government area in Bayelsa State. The nine (9) pieces of plantain were taken to the Agricultural and Environmental Engineering Department Processing Laboratory, Niger Delta University, Wilberforce Island, Bayelsa State, Nigeria, the Niger Delta University is located from Latitude 4°51'N to 5°02'N, and from longitude6°.04'E to 6°17'E. The plantains were washed thoroughly with clean water and was peeled manually using a stainless-steel knife. The Vernier calliper was used to measure the thicknesses of the plantain thicknesses were 3mm, 4mm and 5mm using a stainless-steel knife. Thereafter the sliced plantains of each thicknesses were placed in the oven within the temperature ranging from 60°C, 70°C and 80°C, three (3) set of the samples were placed in each of the Oven and were monitored at time intervals of ten (10) minutes and was weighed with a digital weighing balance see plate 5. At each temperature setting, each drying test was repeated three times, and average results were recorded. The final moisture content for each replicate was calculated using the weight variations between before and after drying. Using equation 1

$$\mathrm{MR} = \frac{\mathrm{M} - \mathrm{M_e}}{\mathrm{M_o} - \mathrm{M_e}} \qquad .1$$

The Fick's second law diffusion equation was used to transform the bioproduct sample geometry, which was assumed to be somewhat cylindrical, in order to obtain the equivalent moisture ratios as (Guine *et al.*, 2011; Motevali *et al.*, 2012; Chen *et al.*, 2013).

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

$$d_c = (\mathrm{L} \times \mathrm{W} \times \mathrm{T})^{\frac{1}{3}}$$ (Mohsenin, 1986)

As the major, intermediate, and minor diameters of the biomaterials, L (length), W (width), and T (thickness), respectively, the factor dc is the dimensional estimator for these dimensions. Then Equation 3. will now give as (Guine *et al.*, 2011)

$$\mathrm{MR} = 0.8106 \int_{n=1}^{\infty} {\varepsilon_n}^{-2} e^{-9.87 \varepsilon_n \left(\frac{D_e t}{{r_c}^2}\right)} \qquad 3$$

where $\varepsilon_n = n^2$

Equation 3 has a tendency to converge on the integration operation over a long drying time (t). When drying cylindrical products in thin layers, the first term seems to dominate, making the other terms in the series too small to be taken into account and resulting in Equation 4. (Burubai, 2015; Babalis & Belessiotis, 2004; Zogzas *et al.*, 1996)

$$MR = 0.8106e^{-9.87(\frac{D_e t}{r_c^2})} \tag{4}$$

Taking natural log on both sides, equation 4 will linearize to

$$\ln(MR) = -(47De(\frac{1}{R_c})^2 t + 1) \tag{5}$$

2.3.1. Effective Moisture Diffusivity, D_e

Drying parameter can be determined 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)

$$De = -slope\frac{[r_c^2]}{47} \tag{6}$$

2.3.2. Activation Energy, E_a

It is known as activation energy when it comes to the energy needed to start molecular diffusion and cause drying in biomaterials. An Arrhenius-type function was utilized to calculate the activation energy because in this work temperature, t is a measurable parameter as (Saxena & Dash, 2015; Da Silva *et al.*, 2015).

$$(De = Do = e^{-E_a/Rt}) \tag{7}$$

where

E_a = activation energy, kJ/mol

D_e = effective diffusivity at m^2/s.

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

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

t = air temperature expressed in T

Simplification of Equation 7 gives

$$\ln De = \ln Do -= \frac{E_a}{R}t^{-1} \tag{8}$$

or

$$-\frac{E_a}{R}t^{-1} = \ln D_e - \ln D_o \tag{9}$$

$$\frac{E_a}{Rt} = \ln(\frac{D_o}{D_e}) \tag{10}$$

$$\frac{E_a}{R}t^{-1} = \ln(\frac{D_o}{D_e}) \tag{11}$$

Plotting of $\ln D_e$ as a function of t^{-1}) that can be given as;

$$z = -\frac{E_a}{R} \text{ (as in Equation 22)} \tag{12}$$

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

$$E_a = -zR \qquad 13$$

2.3.3 Thin Layer Drying Models

In order to calculate the dimension less moisture ratio of the samples, the experimental drying data of ripe plantains obtained during drying in a food processing laboratory at various temperatures was fitted into three widely used Thin-Layer drying models. Using models in Table 1.

Table 1: Various Thin-Layer Models

Model Name	Model	Linearised model	Equation	References
Lewis	MR =exp(-kt)	$R = exp(-kt)$	14	Doymaz and Ismail (2011)
Page	MR =exp(-kt^n)	$\log(-\ln(MR)) = n\log t + \log k$	15	Jangan *et al.*, (2008)
Henderson and pabis	MR = aexp(-kt)	$MR = aexp(-kt)$	16	Figiel (2010)

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

From table 1. Henderson and Lewis models, a plot of InMR versus time was used for the determination of the constants and coefficients. Additionally, the constants and coefficients were fitted into the non-linear model mentioned earlier to determine the predicted moisture ratios in accordance.

For Page model, log(-In(MR)) versus logt was used for the determination of the constants and coefficients. Using the aforementioned constant and coefficient, the predicted moisture ratios were computed by incorporating them into the non-linear models.

2.3.4 Drying Rate

In order to determine how quickly samples dried using equation 17

$$DR = \frac{M_{t+\Delta t} - M_t}{\Delta t} \qquad 17$$

2.3.5 Statistical Analysis

The root mean square error (MSE), reduced chi-square (X^2), and coefficient of determination (R^2) parameters were used to assess how well the tested mathematical model represented the experimental data. The standard is that a fitting is better when the R^2 value is higher and the

(MSE) and X^2 values are lower (Wang *et al.*, 2007: Ozbek & Dadah, 2007). The following mathematical definition applies to the aforementioned parameters:

$$R^2 = 1 - \left[\sum_{i=1}^{n}(MR_{pre,i} - MR_{exp,i})^2\right] \qquad 18$$

$$\text{Root Mean Square (RMSE)} = \sqrt{\frac{\sum_{i=1}^{n}(MR_{pre,i} - MR_{exp,i})^2}{n}} \qquad 19$$

$$\text{Reduced Chi-square } (\chi^2) = \frac{\sum_{i=1}^{n}(MR_{pre,i} - MR_{exp,i})^2}{n - k} \qquad 20$$

3.0 RESULTS AND DISCUSSION

3.1 Dehydration Kinetics Ripe Plantain *(musa paradisiaca)*

Figure 1, 2 and 3 illustrate the drying values obtained in the samples at different slice thicknesses, indicating that the moisture ratio of the sample decreased as drying time increased because of the high systemic water tangentially approach the drying curve to the drying time is slow. The sluggish pattern of the curve also revealed that there was no case-hardening in the high temperature regions during the dying phase.

The drying rate of Ripe Plantain *(musa paradisiaca)* indicates that internal diffusion regulates the rate of drying during the period of falling rate. This is consistent with the findings of (Burubai & Bratua 2015) on fresh water frogs, (Zibokere & Egbe 2019) on red palm weevil larvae, (Davies *et al.*, 2020) on shrimps, youghour (Hayaloglu *et al.*, 2007), red pepper (Akpinar *et al.*, 2003), fresh fish (Burubai & Bratua 2015); (Kilic, 2009); (Zibokere & Egbe 2020) for Spiced Okpokuru

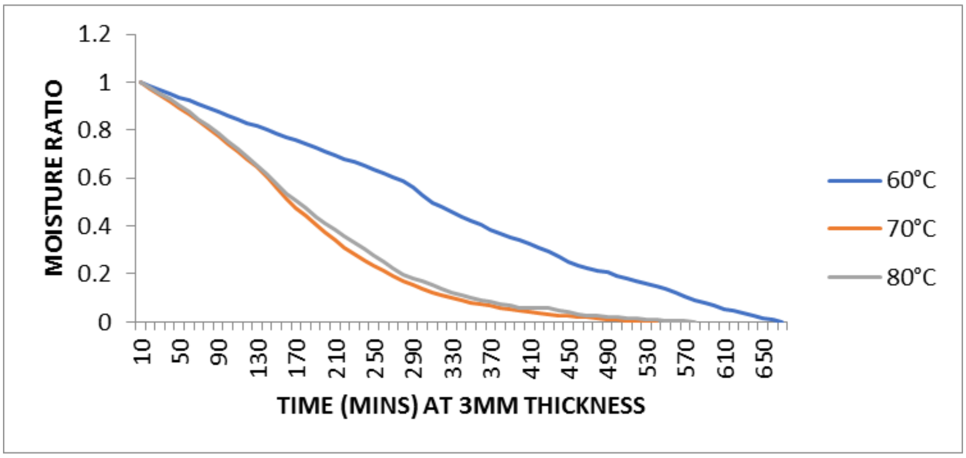

Figure.1: A a graph showing the moisture ratio versus the drying time for a 3mm slice thickness

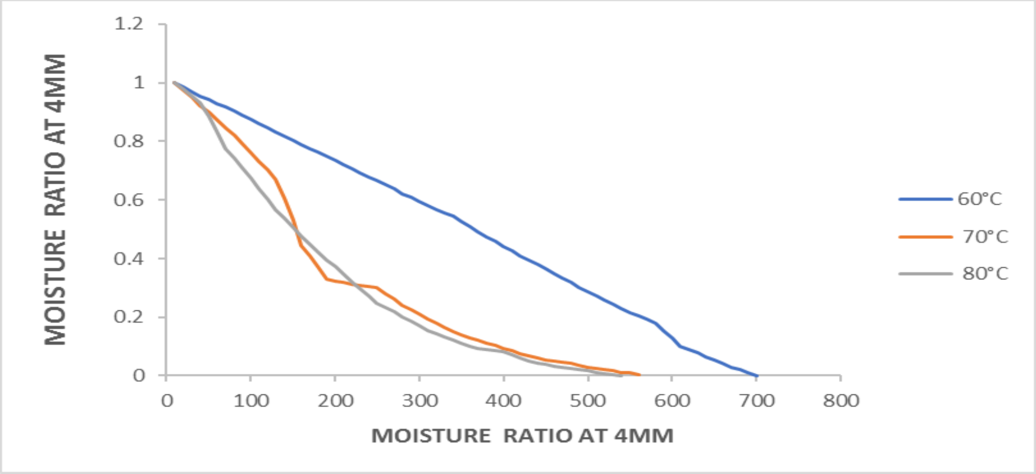

Figure 2. A a graph showing the moisture ratio versus the drying time for a 4mm slice thickness

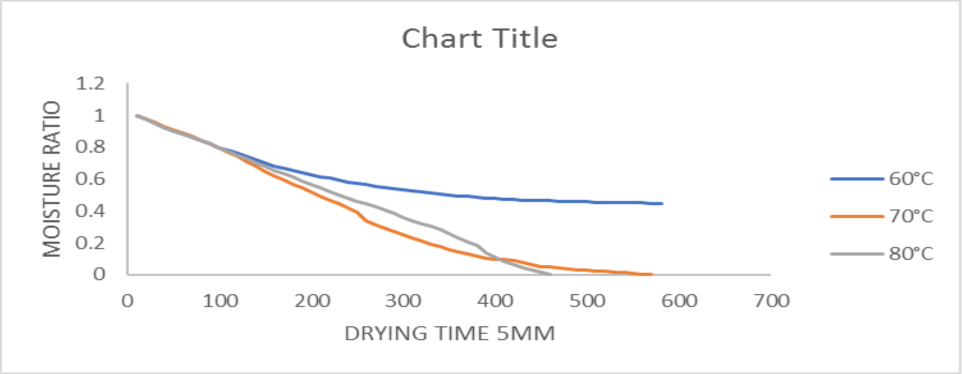

Figure. 3. A graph showing the moisture ratio versus the drying time for a 5mm slice thickness

3.2 Fitting Experimental Data into Drying Curve for Ripe Plantain

The experimental drying values were calculated using three distinct models the Page model, the Henderson-pabis model, and the Lewis model. The fitting was done to see out which model would best depict the Ripe Plantain. The data were fitted into Fick's second law of diffusion equation, and the constant 'k', as well as the coefficients 'a' and 'n', were calculated using a non-linear least squares approach (SPSS 1996) see table 3. The plot of the moisture ratio experimental against the moisture ratio predicted was used to determine the coefficient of determination (R2), the root mean square (RMSE), the mean bias error (MBE), and the reduced square error (X2), which were then calculated and are shown in tables 2 and 3. The model with the lowest RMSE, X^2, and highest R^2 was chosen as the most appropriate model to represent the specimen drying feature. Henderson-pabis model followed by Page model were shown to be the best fit to forecast the drying feature of Ripe Plantain (musa paradisiaca) among the three models used in this study.

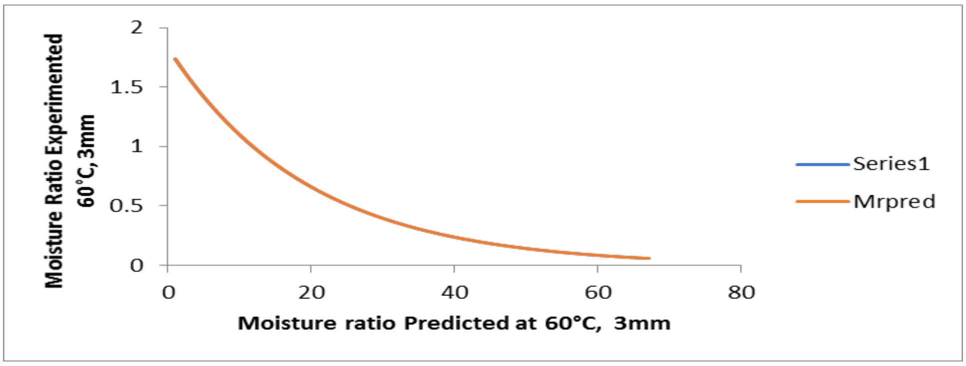

Figure 4. Henderson model predicted moisture ratio at 60°C and its relationship with experimental moisture ratio.

Table 2 Statistical results of the ripe plantain

MODELS	TEMP◦C	THICKNESS	R²	RMSE	X²
	60°c	3mm	0.9987	0.000437	0.00001938810
	60°c	4mm	0.9992	0.000346	0.000113555
	60°c	5mm	0.9996	0.000618	0.0000000447730
HENDERSON MODEL	70°c	3mm	0.9974	0.006882	0.000482626
	70°c	4mm	0.9969	0.00738	0.00005543
	70°c	5mm	0.9723	0.021838	0.000485281
	80°c	3mm	0.9973	0.006808	0.00000471582
	80°c	4mm	0.9064	0.041629	0.001765712
	80°c	5mm	0.9973	0.00689	0.000049204700
PAGE MODEL	60°c	3mm	0.9547	0.026203	0.000697157
	60°c	4mm	0.9231	0.033389	0.001131219
	60°c	5mm	0.9311	0.039135	0.001566373
	70°c	3mm	0.9837	0.017521	0.000312873
	70°c	4mm	0.9853	0.016204	0.000267327
	70°c	5mm	0.9568	0.027526	0.000771199
	80°c	3mm	0.9848	0.016322	0.000271171
	80°c	4mm	0.9888	0.014379	0.000214708
	80°c	5mm	0.9351	0.034051	0.00118057
LEWIS MODEL	60°c	3mm	0.9626	0.023642	0.000567404

	60°c	4mm	0.9571	0.02755	0.000621679
	60°c	5mm	0.9632	0.028295	0.000818406
	70°c	3mm	0.9772	0.020557	0.000430544
	70°c	4mm	0.9883	0.014338	0.000209245
	70°c	5mm	0.994	0.010213	0.00010613
	80°c	3mm	0.8971	0.042485	0.000183721
	80°c	4mm	0.9857	0.016255	0.000269195
	80°c	5mm	0.9693	0.023195	0.000547613

Table 3 Statistical constant and coefficient results of the ripe plantain

MODEL	TEMP◦C	THCKNESS	K	a	N
HENDERSON MODEL	60°c	3mm	0.0051	1.7519	
	60°c	4mm	0.0044	1.696725	
	60°c	5mm	0.0066	1.831069	
	70°c	3mm	0.0101	2.162143	
	70°c	4mm	0.0082	1.769328	
	70°c	5mm	0.0014	1.130206	
	80°c	3mm	0.0094	2.139132	
	80°c	4mm	0.0086	1.765617	
	80°c	5mm	0.0084	2.144057	
PAGE MODEL	60°c	3mm	1.3578		0.000355
	60°c	4mm	1.4565		0.000157
	60°c	5mm	1.4545		0.000295
	70°c	3mm	1.6245		0.000184
	70°c	4mm	1.5435		0.000253
	70°c	5mm	0.9151		0.003065
	80°c	3mm	1.6204		0.00017
	80°c	4mm	1.5207		0.000314
	80°c	5mm	0.6143		0.10493

LEWIS MODEL	60°c	3mm	0.0051
	60°c	4mm	0.0044
	60°c	5mm	0.0066
	70°c	3mm	0.0101
	70°c	4mm	0.0082
	70°c	5mm	0.0014
	80°c	3mm	0.0094
	80°c	4mm	0.0863
	80°c	5mm	0.0084

3.3. Effective Moisture Diffusivity, (De.) Ripe Plantain (musa paradisiaca)

The effective moisture diffusivity De is an important input variable that depicts the effective moisture migration from the specimen surface. With the measured thicknesses of 3mm, 4mm and 5mm a plot of In(MR) against drying time was calculated, yielding a slope.as showed in figures 5-7 as the temperature rises from 60°C through 80°C, the average of three replications rises from 3.23 $\times 10^{-6}$ – 6.0 for 3mm, 3.6 6.3 $\times 10^{-6}$ KJ/mol for 4mm and 7.0 $\times 10^{-6}$ – to 8.9 $\times 10^{-6}$ KJ/mol for 5mm. Table 4 shows the average values moisture diffusion as it rises with increasing temperature, according to research. Jittanit 2011; Robert *et al.,* 2018; Burubai & Bratua (2015); Zibokere & Egbe (2021). for example, all had identical findings on pumpkin seeds, grape seeds, fresh water claims and fresh water clawed lobster.

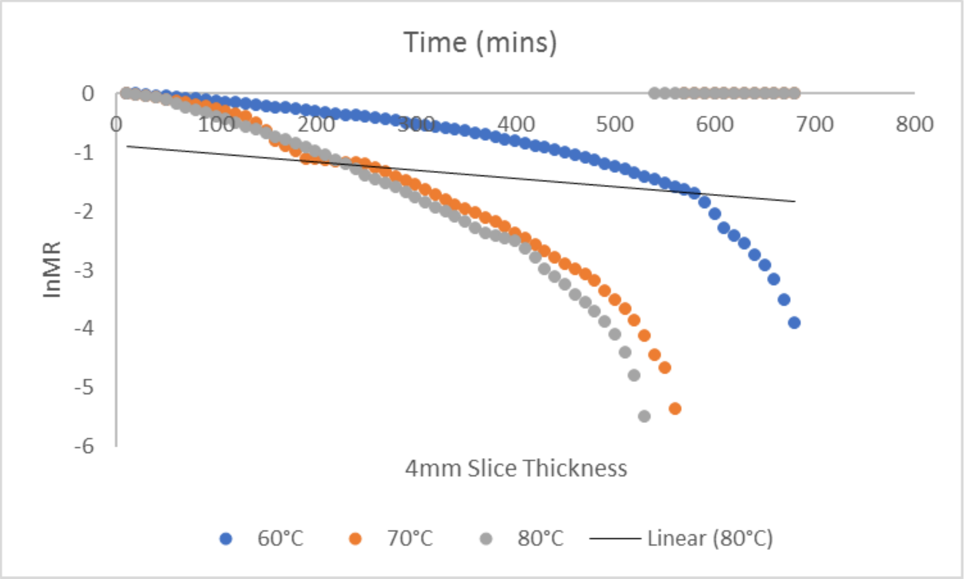

Fig. 5. Slice thickness of 4 mm and drying curve of ripe plantains

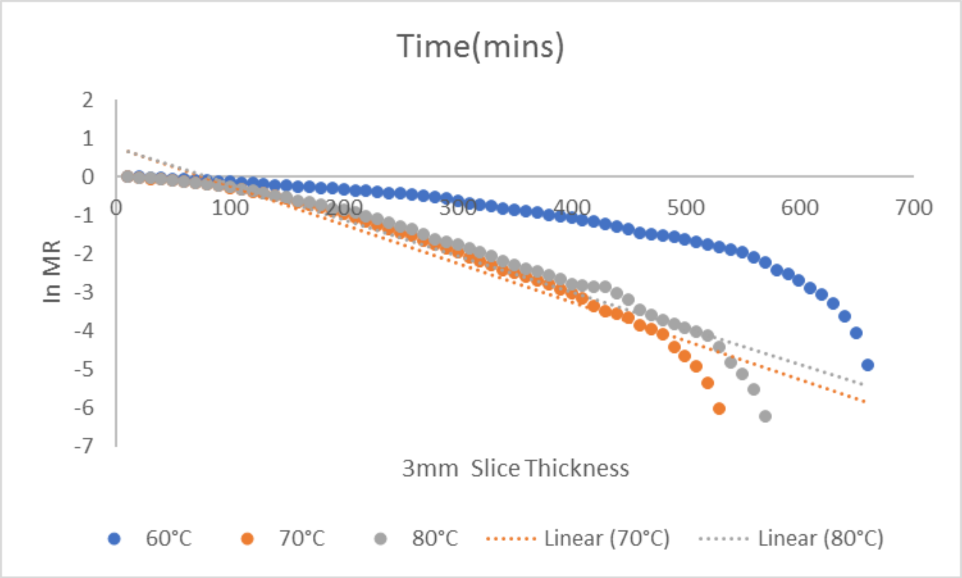

Fig. 6. Slice thickness of 3 mm and drying curve of ripe plantains

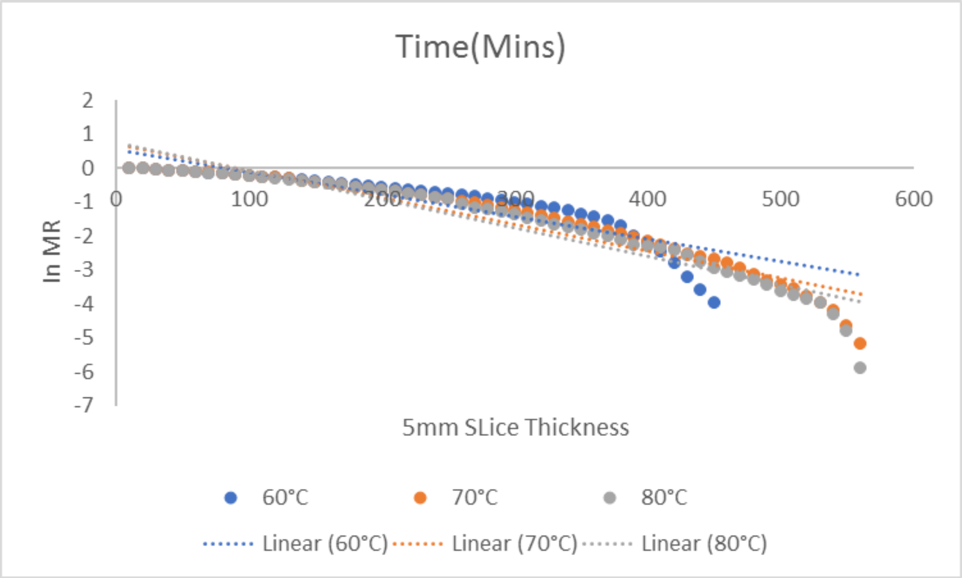

Fig. 7. Slice thickness of 5 mm and drying curve of ripe plantains

Table 4 Ripe plantain moisture diffusivity values

Temperature °C	**Slice Thicknesses**	**Average Effective Moisture Diffusivity m^2/s**
60	3mm	3.3×10^{-6}
70	3mm	6.4×10^{-6}

80	3mm	6.0×10^{-6}
60	4mm	3.6×10^{-6}
70	4mm	6.8×10^{-6}
80	4mm	1.2×10^{-6}
60	5mm	7.0×10^{-6}
70	5mm	8.4×10^{-6}
80	5mm	8.9×10^{-6}

3.4. Evaluation of Activation Energy.

This is the very minimal amount of energy necessary to dry Ripe Plantain It can be found by linearizing the Arrhenius equation within the temperature range specified for this study. The higher the 'Ea,' the longer it will take to reach the target moisture level. The Ea in this study were investigated to be 9.20kJ/mol, 11.25KJ/mol and 14.5KJ/mol for 3, 4 and 5mm slice thicknesses respectively. It was found that the more the slice thickness increased, the more activation energy was needed. The results in the literature range from 12.7-110k-J/mol for high moisture biomaterials (zogzas *et al.,* 1996) to 0-53k-J/mol for low moisture biomaterials (zogzas *et al.,* 1996). (Toakis & Labuza 1989), Zibokere & Egbe (2019) Red palm weevil.

Table 5. The Impact of Drying on Activation Energy and Slice thicknesses

Slice Thickness (mm)	Activation Energy (KJ/mol)
3	9.2
4	11.25
5	14.5

4. CONCLUSION

An investigation into the drying kinetics of ripe plantains revealed that, like other biological materials, the drying process is subject to a falling rate period. Fitting the outcomes to the three thin-layer models using the parameters allowed for the selection of an appropriate estimating thin-layer model (R2, RMSE, and X2). Henderson model R^2 ranged from 0.9064-0.996, RMSE ranged from 0.021838-0.000346 and X^2 ranged from 0.0017765712-0.0000000447730. The model chosen as the best fit to describe the drying characteristics of ripe plantains had the lowest RMSE, highest X^2, and highest R^2 values. Henderson model and closely followed by page model models that give the lowest RMSE and X^2, and the highest R^2 values and are accordingly accepted as representing the dry characteristic of the ripe plantain having the drying parameter subjected to statistical analysis. The Ea in this study were investigated to be 9.20kJ/mol, 11.25KJ/mol and 14.5KJ/mol for 3, 4 and 5mm slice thicknesses respectively. Activation energy tends to increase with an increase in slice thickness and effective moisture diffusivity also increased with an increased in temperature.

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