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Research Article

EVALUATION OF DRYING CHARACTERISTICS AND THERMOPHYSICAL PROPERTIES OF UNRIPE PLANTAIN

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ABSTRACT
In this study, plantain chips were dried at 50, 60 and 70 ^{o}C in a laboratory tunnel dryer. Kinetics of drying was investigated using Fick's second law and nonlinear regression analysis was used to fit in the experimental data. The model reliability was tested using coefficient of determination (R^2), Root Mean Square Error (RMSE) Mean Bias Error (MBE) and reduced chi square (χ^2). The proximate, bulk density and thermal properties were also investigated.
The results show that the range of values of statistical criteria were R^2: (0.847-0.997), RMSE (0.01869-0.03418), MBE (-6.92E-3-0.03619) and (χ^2) (1.3E-4-3.52E-3) The proximate result showed that the range of values were: moisture (8.15-11.47%), protein (3.61-5.15), lipid (0.20-0.78), fibre (3.27-4.56%), ash (4.47-6.91%) and carbohydrate content (74.13-74.62%). The range of values for bulk density were (544.01- 628.02 kg/m^3), specific heat capacity (1.68 - 1.76 KJ/g K), thermal conductivity (0.253-0.267W/K) and thermal diffusivity (0.0242 - 0.0278m^2/s).
In conclusion, the drying rate increased with increase in temperature and drying pattern was observed to be in the falling rate period. R^2 showed that page model best described the drying behaviour of the samples. Proximate decreased with increase in temperature but ash content increased with increase in temperature. The bulk density, specific heat capacity, and thermal conductivity decrease with increase in temperature while thermal diffusivity increase as temperature increased.

Keywords: *Unripe Plantain, Drying Kinetics, Proximate Composition, Thermal Properties*

INTRODUCTION
Plantain (*Musa paradisiaca*) is an important staple food in Central and West Africa along with banana provides 60 million people with 25% of their calories. It is grown in 52 countries with world production of 33 million metric tons (FAO 2005). Locally, plantain constitutes about 13% of the countries agricultural gross domestic product (SRID-MOFA, 2006), and ranks third in volume of production among starchy staples. In the agricultural sectors, plantain is ranked fourth (FAO, 2005).
Over 2.11 million metric tons of plantains are produced in Nigeria annually. However, about 35-60% post-harvest losses have been reported and attributed to lack of storage facilities and inappropriate technologies for food processing. A large quantity of unmarketable surplus is available in the plantain growing areas and very few processed products are marketed. Processing of plantain into diverse products with longer shelf life such as fruit, powder, puree, chips, and beverages has been proposed as a way of absorbing seasonal surpluses and thus increasing and stabilizing farmers' income (Balasooriya *et al*., 2006).
Drying is a common practice for preserving plantain in order to make it available throughout the year (Eklou *et al*., 2006). Sun, oven, and solar drying are the popular drying methods used in drying this food crop. Sun drying being the most common but has the problem of fluctuating weather. That is why

mechanical dryer such as tunnel dryer is employed to dry food material which produces better food product. This food crop, when dried is processed to produce flour which can be reconstituted to form paste or dough (Emperatiiz *et al*., 2008).

Over the years, research effort has been directed towards the study of various engineering properties of food crops especially those properties that influence its drying and the design of equipment for processing. Generally, the variation in temperature and concentration of plantain fruit during processing greatly affects its thermal properties. Some important thermal properties of plantain include thermal conductivity (k), specific heat (Cp) and thermal diffusivity (α) and these are useful in the design of drying equipment. Hence, the objectives of the study are to investigate the drying kinetics of plantain chips using mathematical modelling of thin layer drying and to determine its thermo-physical properties.

MATERIALS AND METHODS

Matured green unripe plantain popularly known as 'Agbagba Erin' was purchased from a local market in Ogbomosho, Oyo state, Nigeria. All the other equipment and reagents used were obtained from Food Engineering Department LAUTECH Ogbomosho.

Drying Experiment

Green matured plantain fruits was washed to remove adhering soil particles, peeled and sliced into thin thickness of 5mm. The drying experiment was performed in a tunnel dryer. The dryer was operated at air temperature of 50, 60 and 70^{o} C at constant air velocity of 1.5m/s. The temperature and the air velocity in the dryer were at steady state before samples were introduced into the dryer. Rectangular plantain chips were selected for the drying operations. The samples was placed in the dryer and removed manually every 1 hour to determine weight loss of the sample. The drying experiment stopped when three consecutive sample weights remained constant. The dried sample was packaged in a properly labelled air–tight polythene bag for further analysis.

Mathematical models

In this work, Fick's second law of moisture diffusion in porous media was adapted for the drying operation. This is as represented in Equation 1

$$\frac{\partial m}{\partial t} = D\frac{\partial^2 m}{dt^2} \qquad 1$$

Where m = moisture content (kg water/kg solid); t = time (s); D = diffusion coefficient for moisture in solids (m^2/s).

To solve this equation for rectangular shapes, the following assumptions are made;

- Free water content at the surface is zero and moisture is evenly distributed.
- The shape and size of the sample remain constant during drying i.e. negligible shrinkage.
- Heat transfer proceeds very quickly (negligible internal and external heat transfer effect).

These models in Table 1 show relationship between moisture ratio and drying time. Moisture ratio (MR) during the thin layer drying was obtained using Equation 2

$$MR = \frac{M_i - M_e}{M_0 - M_e} \qquad 2$$

Where MR= dimensionless moisture ratio, M_i = instantaneous moisture content (g water/g solid), M_e = equilibrium moisture content (g water/ g solid), M_o = initial moisture content (g water/ g solid). However, due to continuous fluctuation of relative humidity of the drying air in the dryer, Equation 2 is simplified in Equation 3 according to Goyal *et al.*, (2007).

$$MR = \frac{M_i}{M_0} \qquad 3$$

Determination of effective moisture diffusivity

The simplified equation of Fick's second law was adapted to determine the moisture diffusion from the plantain samples during the drying process. The analytical solution of the Equation 4 represents the mass transfer of a rectangular shape.

$$MR=\frac{M-M_0}{M_0-M_e}=\frac{8}{\pi^2}\sum_{n=0}^{n=1}\frac{1}{(2n-1)^2}exp\ \frac{-(2n-1)^2\pi^2 Deff\ t}{4l^2} \quad 4$$

Where D_{eff} is the moisture diffusivity (m^2/s), t is the drying time (s), l is the half of the slab thickness (m), MR = dimensionless moisture ratio, M_i = instantaneous moisture content (g water/g solid), M_e = equilibrium moisture content (g water/ g solid), M_o = initial moisture content (g water/ g solid). However, due to continuous fluctuation of relative humidity of the drying air in the dryer, Equation 4 is simplified in Equation 5 according to Goyal *et al.*, (2007).

$$MR=\frac{Mi}{Mo}=\frac{8}{\pi^2}\sum_{n=0}^{n=1}\frac{1}{(2n-1)^2}\exp\frac{-(2n-1)^2\ \pi^2 D_{eff}\ t}{4l^2} \quad 5$$

The effective moisture diffusivity (D_{eff}) was calculated from the slope of plot of natural logarithms (ln) MR against drying time (t) according to Doymas, (2004) and is represented in Equation 6

$$k=\frac{\pi^2 Deff}{4l^2} \quad 6$$

Where *k* represents the slope of the graph.

Determination of activation energy

Arhenius equation describes the relationship between moisture diffusion and temperature of drying. This relationship is as shown in Equation 7.

$$D_{eff=D_0\ exp\frac{-E_a}{RT}} \quad 7$$

Where D_0 is the pre-exponential factor of the Arrhenius equation in m^2 /s, E_a is the activation energy in kJ/mol, R is the universal gas constant in kJ/mol K and T is the absolute air temperature in K. The activation energy will be calculated by plotting the ln of D_{eff} against inverse of the absolute temperature.

Table 1: **Mathematical drying models**

Models	Equation	References
Henderson and Pabis	MR=aexp(-kt)	Bhuchiss *et al*, (2008)
Newton	MR=exp(-kt)	Kingly *et al.*, (2007)
Page	MR=exp($-kt^n$)	Karathanos and Belessiotis, (1999)
Midilli	MR=aexp($-kt^n$) +bt	Togrul and Pehlivan, (2003)

Statistical analysis

The drying model constants were estimated using a non-linear regression analysis. The analysis was performed using Statistical Package for Social Scientist (SPSS 20.0 versions) software. The reliability of these models was verified using statistical criteria such as coefficient of determination (R^2), reduced chi-square (χ^2), root mean square error (RMSE) and Mean Bias Error (MBE). The comparison criteria method can be determined as follows:

$$X^2 = \sum_{i-1}^{n}\frac{(MR_{(exp,.i)}-MR_{(pred,i)})^2}{N-z} \quad 8$$

$$MBE=\frac{1}{N}\sum_{i=1}^{n}(MR_{pred,i)}-MR_{(exp,i)} \quad 9$$

$$RMSE=\left[\frac{1}{N}\sum_{i=i}^{n}(MR_{(pred.i)}-MR_{(exp.i)^2}\right]^{1/2} \quad 10$$

Determination of Proximate, Functional and Thermal Properties

Proximate analysis was carried out using Association of Analytic Chemists (AOAC, 2012) method.

Determination of bulk density

10ml capacity of graduated measuring cylinder was measured, the cylinder was gently filled with the sample and the bottom of the cylinder is tapped several times on the laboratory bench until there is no further diminution of the sample level after filling the 10ml mark.

$$\text{Bulk Density} = \frac{\text{weight of sample}}{\text{Volume of sample}} \quad 11$$

Determination of Thermal Conductivity

The thermal conductivities of the samples were determined using the expression developed by Sweat (1986).

$$K = 0.25\,X_c + 0.155\,X_p + 0.16\,X_f + 0.135\,X_a + 0.58\,X_w \quad 12$$

Where K is thermal conductivity of sample in W/m °C and X are the respective mass fractions of carbohydrate, protein, fat, ash and water present in each sample.

Determination of Specific Heat Capacity

The specific heat capacities of the samples were obtained from the method of Choi and Okos (1986).

$$C_p = 4.180X_w + 1.711X_p + 1.929X_f + 1.547X_c + 0.908\,X_a \quad 13$$

Where C_p is the specific heat capacity in KJ/Kg K and X are the respective mass fractions of water, protein, fat, carbohydrate and ash present in each sample and obtained from proximate compositions.

Determination of Thermal diffusivity

Thermal diffusivity α, (m^2/s), defines the rate at which heat diffuses by conduction through a food composite, and is related to *k* and C_p through density ρ (kg/ m^3) as follows:

$$\alpha = k/\rho C_p \ (m^2/s) \quad 14$$

RESULTS AND DISCUSSION

Table 2: Values of statistical Parameters using non-linear regression

Models	**Temp.**	R^2	χ^2	**MBE**	**RMSE**
Henderson and Pabis	50	0.986	0.00075	0.00812	0.02351
	60	0.994	0.00064	0.00892	0.02563
	70	0.991	0.00102	0.01124	0.03100
	Average	0.990	0.00074	0.03619	0.02671
Newton	50	0.992	0.00059	0.00148	0.03002
	60	0.993	0.00071	0.00417	0.03161
	70	0.984	0.00099	0.00116	0.03418
	Average	0.989	0.00076	0.00227	0.03194
Midilli	50	0.847	0.00074	0.00153	0.02790
	60	0.893	0.00089	0.00323	0.02984
	70	0.955	0.00092	0.00516	0.03071
	Average	0.898	0.00352	0.00331	0.02930
Page	50	0.994	0.00013	– 0.00411	0.01869
	60	0.997	0.00021	– 0.00679	0.01994
	70	0.992	0.00059	– 0.00692	0.02081
	Average	0.994	0.00031	– 0.00594	0.01981

NB: *A good fit occurs* R^2 *is high and* χ^2*, RMSE, MBE values are low*

Table 3: Value for model constants

Model	Temp.	n	a	b	K
Henderson and Pabis	50		1.005		0.276
	60		1.008		0.293
	70		1.031		0.362
Newton	50				0.263
	60				0.288
	70				0.327
Midilli	50	1.141	0.823	– 0.021	0.068
	60	– 0.073	– 0.043	– 0.036	0.003
	70	– 0.041	– 0.947	– 0.119	0.009
Page	50	1.028			– 0.285
	60	0.913			– 0.277
	70	-0.871			– 0.271

Table 4: Value of effective moisture diffusivities at different temperature

Drying air velocity (m^2/s)	Drying air temperature (^{o}C)	Effective moisture diffusivity (D_{eff} x 10^{-10} m^2/s)
1.5	50	1.8958
1.5	60	2.3953
1.5	70	2.9959

Table 5: Proximate composition of plantain flour at different temperature

Sample	**Protein**	**Moisture content**	**Ash**	**Fibre**	**Lipid**	**Carbohydrate**
A	5.15 ± 0.32[a]	11.47±0.83[b]	4.47±0.02[a]	4.56±0.46[a]	0.78±0.01[a]	74.62±0.08[a]
B	4.59±0.70[ab]	10.14±0.59[b]	5.34±0.03[ab]	3.98±0.61[a]	0.28±0.06[b]	74.68±0.78[a]
C	3.61 ± 0.35[b]	8.15±0.33[a]	6.91±0.96[b]	3.27±0.36[a]	0.20±0.19[b]	74.13±0.12[a]

Values are means ± standard deviation. The values in a row followed by the same letter in a column are not significantly different from each other (P>0.05)
Sample A = Dried at 50℃, Sample B = Dried at 60℃, Sample C = Dried at 70℃

Table 6: Functional and thermo-physical properties of plantain flour

Temperature (^{o}C)	Thermal Conductivity (w/k)	Specific Heat Capacity (KJ/kgK)	Thermal Diffusivity (m^2/s)	Bulk density (kg/m^3)
50	0.267±0.001[b]	1.76±0.03[b]	2.42E-4±2.1E-6[a]	628.46±6.95[b]
60	0.260±0.004[ab]	1.73±0.02[ab]	2.52E-4±4.20E-6[a]	601.21±10.02[b]
70	0.253±0.011[a]	1.68±0.04[a]	2.78E-4±1.27E-6[b]	544.01±25.86[a]

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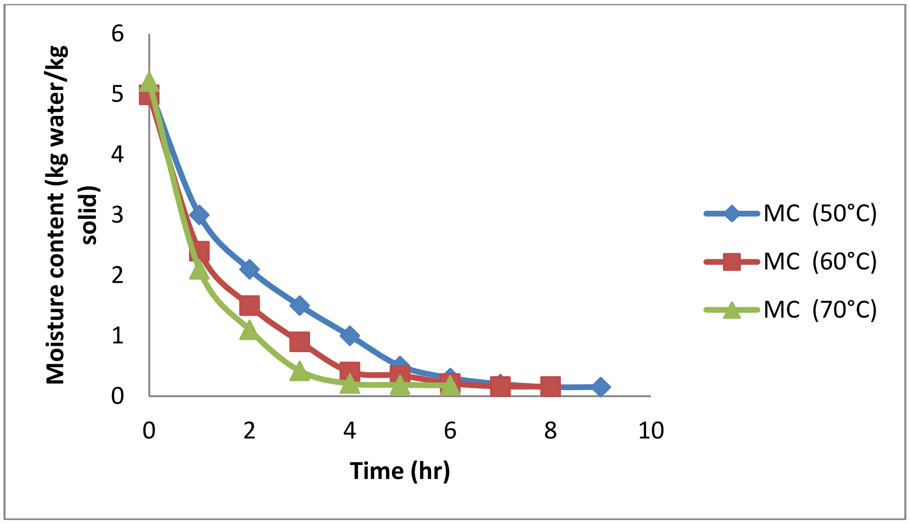

Figure 1: Graph showing moisture content against time

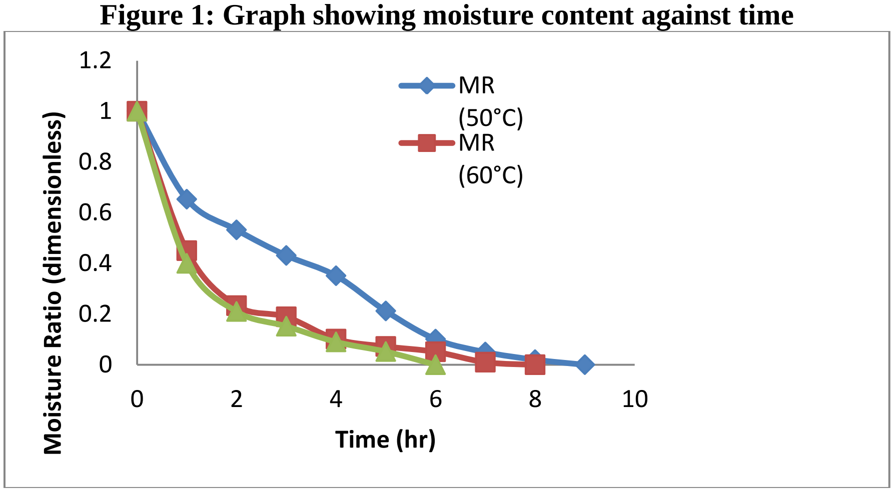

Figure 2: Graph showing moisture ratio against time

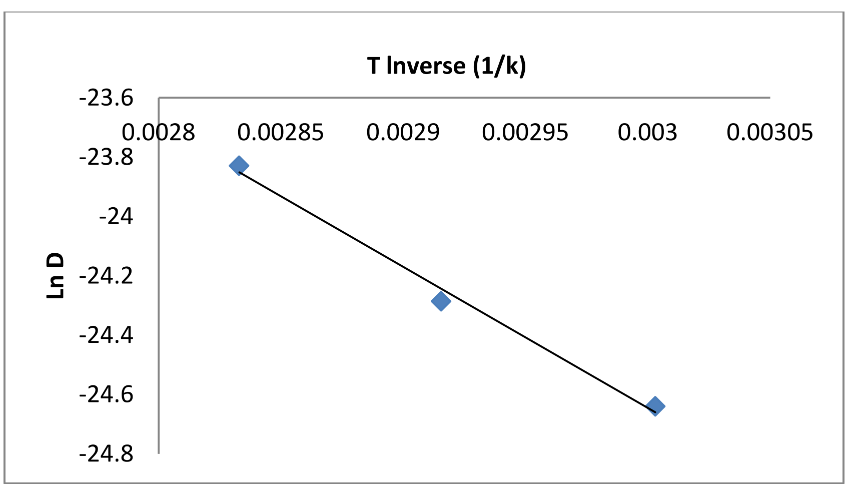

Figure 3: Temperature inverse against ln D

RESULTS

The values of statistical criteria used to evaluate the models are as presented in Table 2. The acceptability of these models is based on the high values of R^2 and low values of the other statistical criteria as shown. From the table, careful analysis of the average R^2 for each is as follows: Handerson and Pabis; 0.990, Newton; 0.989, Midilli; 0.898, Page; 0.994. These values showed that page model had the highest average value of R^2 while the lowest value of R^2 is 0.898 (Midilli model). The lowest value of $\chi 2$ is 0.00013 (Page model) while the highest value is 0.00352 (Midilli model). The lowest value of MBE is -0.00679 (Page model) while the highest value is 0.03619 (Henderson and Pabis model). The detail values of constants of the models are presented in Table 3. Letters *n, a b* and *k* represent the available constant in the models with highest value of 1.141 in *'n'* constant and lowest value of – 0.285 in *'k'* constant. Also, the values of moisture effective diffusivity (D_{eff}) are shown in Table 4. The values are stated as $1.8959\text{x}10^{-10}$ m^2/s at 50^o C, $2.3959\text{x}10^{-10}$ m^2/s at 60 ^{o}C and 2.9959 m^2/s $\text{x}10^{-10}$ at 70 ^{o} C. The data showed that moisture diffusion is temperature dependent. Furthermore, the energy needed to bring about drying plantain at three temperatures was deduced from the plot of natural logarithm of effective diffusivity (lnDeff) against the inverse of absolute temperature (1/T).

The result of proximate composition of plantain was as presented in Table 5. Drying using tunnel dryer at different temperature has significant influence on all the determined chemical properties at 95% confidence level. The crude protein content of the sample dried at 50, 60 and 70 ^{o}C were 5.15% ± 0.32, 4.59%±0.70 and 3.61% ± 0.35 respectively, sample dried at 50^0C has the highest protein content while sample dried at 70^oC has the lowest protein as shown in the table. The results of functional and thermo physical properties are as shown in Table 6. Thermal conductivity, specific heat capacity, thermal diffusivity and bulk density range values are:0253-0.267 w/k, 1.68-1.76 kJ/kgK, 2.78E-4 to 2.42E-4 m^2/s and 544.01- 628.46 kg/m^3, respectively. These values show that the values increased as the moisture content increased for the various drying temperatures.

The pattern of moisture loss in the sample is as shown in Figure 1. From the graph, the value decreased generally from moisture content of 5 kg of water/kg solid to 0.18 kg water/kg solid. Figure 2 shows the pattern of dimensionless moisture ratio against drying time. The value decreased generally from 1.0 to 0.02. From the slope of the resultant straight line Figure 3, activation energy (E_a) for diffusion of water of the plantain was calculated to be 45.21 KJ/mole.

DISCUSSION

Statistical analysis of the models

Statistical tools are used to test the reliability of a model, such tool include R2, RMSE, MBE and χ^2. As earlier stated above, the highest R^2 was found in Page model and also the lowest value of RMSE is 0.01869 (Page model).It can therefore be said that the Page model fitted the experimental data better based on the estimation of R^2, X^2 and RMSE. This is because higher values for coefficient of determination (R^2) with corresponding lower values of root mean square error (RMSE) and reduced chi-square ($_X{}^2$) are chosen as criteria for goodness of fit (Ajala *et al.*, 2021, Doymaz, 2007).

Constant '*a*' had lowest and highest values of -0.947 and 1.031 found in Midilli and Henderson-Pabis models respectively. Constant '*b*' had the lowest and highest values of -0.119 and -0.021 found in Midilli model while the highest and lowest values for constant '*k*' were 0.362 and -0.277 found in Henderson-Pabis and Page models, respectively. Furthermore, the highest and lowest values for constant n are 1.141 and -0.871 found in Midilli and Page model, respectively.

The values of constant in models are important to the existence of it such that if other factors change in the models, the reliability of the models will be intact at a given condition.

Determination of Effective Moisture Diffusivity

The value of D_{eff} increased as the temperature increased as shown in Table 4. This might be explained by the increased heating energy, which would increase the activity of the water molecules leading to higher moisture diffusivity when samples were dried at higher temperature. The same observation has been reported by, Ajala, *et al.,* (2012) and Guine *et al.,* (2009). The values of moisture diffusivity in this study was in the range of food products (10^{-7} to 10^{-12}) as reported by (Hii *et al.,* 2009). Doymaz and Akgun (2005) reported effective moisture diffusivity values in the range of 0.3 to 1.1 x $10^{-8}m^2/s$ in a temperature range of 50 to 110^oC and observed that the values increased with increasing temperature. Doymaz (2004) on analysis of the drying kinetics of the white Mulberry reported that moisture diffusivities were affected by pretreatments. Kingly *et al.,* (2007) reported values in the ranged from 1.68 to 2.84 x 10^{-9} m^2/s for thin layer drying characteristics of organically produced tomatoes. The temperature dependence of the effective diffusivity was represented by an Arrhenius relationship through which activation energy could be derived (Ajala *et al*., 2019 and Sanjuan *et al.*, 2003).

Effect of Drying On Proximate Composition

The results of proximate analyses show that they were significantly different ($p<0.05$) in crude protein content of the plantain. This implies that plantain does not rich in proteins. These agree with the report by Salawu *et al*., (2015) in unripe plantain powder. Carbohydrate content of the sample varied from 74.13 $\pm$ 0.12% to 74.62 $\pm$ 0.08%. Sample dried at 60 ^{o}C has the highest carbohydrate content while sample dried at 70 ^{o} C has the lowest carbohydrate content. However, on this basis of comparison, the carbohydrates content between the dried samples was not significantly different ($p<0.05$). The moisture content of flour was determined to be 11.47% at 50 ^{o} C as compared to 10.14% at 60 ^{o} C and 8.15% at 70 ^{o} C. The sample dried at 50 and 60 ^{o} C were not significantly different ($p<0.05$) while the sample dried at 70 ^{o} C had significance differences, ($P<0.05$). Moisture content of foods gives an indication of its anticipated shelf life and low moisture content is a requirement for long storage life. During storage, fungal growth is bound to be observed on moist food samples. Fungal food contamination could be a predisposing factor to food poisoning such as aspergillosis. Since a well dried food sample withstands fungal and other microbial infestation better during storage and making them available throughout the year. Ash is the inorganic residue after the water and organic matter have been removed by drying a food sample. Ash was significantly different ($P<0.05$) between the three samples in Table 5. When subjected to analysis of variance, the results are 4.47±0.02 at 50^{o}C, 5.34±0.03 at 60^o C and 6.91±0.96 at 70 ^{o} C respectively which is in agreement with the 6.99% at 70 ^{o} C reported by Adepoju *et al*., (2012). Also Moris *et al.,* (2004) observed 3.95±0.07 at 50 ^{o} C, 4.25±0.02 at 60 ^{o} C and 5.12±0.03 at 70 ^{o} C. It was shown that sample dried at 70 ^{o} C contain higher ash content while sample dried at 50 ^{o} C contain low ash content. It was observed that the ash content increased with increase in drying temperature. The increase in the ash contents could as a result of the removal of moisture which tends to increase the concentration. Such observation has earlier reported by Yusuf *et al.,* (2017). Fat, indicating the total lipid content of the plantain as shown in Table 5. The values ranged from 0.2-0.78% and sample dried at 60 ^{o} C and 70 ^{o} C were not significantly different, ($p<0.05$), but there was significant difference, ($P<0.05$) from the sample dried at 50 ^{o} C. Variations could be due to intensity of heat during the drying process. Similar observation was reported by Agoyero *et al*., (2011) for unripe plantain fruit with values as 0.90% at 50 ^{o} C, 0.30% at 60 ^{o} C and 0.22% at 70 ^{o} C while Adepoju *et al*., (2012) reported 1.00% at 50^{0}C, 0.50% at 60 ^{o} C and 0.29% at 70 ^{o} C. The decrease in lipid content of the samples could be as a result of lipid oxidation. This is because lipid oxidation is known to be increased by many factors such as heat, sun light and radiations (Savage *et al.,* 2002).

Functional and Thermo-physical Properties

Functional and thermo-physical properties of plantain sample show that they were temperature dependent. Sample dried at 50 and 60 ^{o} C were not significantly different but sample dried at 70 ^{o} C did at ($p<0.05$). The thermal conductivity of the sample at different temperature (50-70 ^{o} C) ranged from 0.25W/k to

0.27W/k with sample dried at 70 ^oC and was significantly different. There was an increase in thermal conductivity as temperature decreased in plantain samples. Other researcher such as Nwabanni (2009) reported the existence of linear relationship between thermal conductivity with moisture content and temperature for other agricultural products. At a moisture content of 63-65% wb, Perusella *et al.* (2010) found that the thermal conductivity of banana using the line heat probe method varied from 0.3-0.55W/m^{o}C. Also, Dithfield *et al*., (2005), found the thermal conductivity of banana puree to be 0.695 W/m K. Thermo-physical properties are significantly dependent on changes in moisture content and temperature (Ajala and Idowu 2016). Thermal conductivity is important to predict or control heat flux and processing time. This ensures the efficiency of equipment, improves economics of the process, and enhances quality product. Thermal diffusivity is a measure of how fast heat propagates or diffuses through a material. The thermal diffusivity of the samples ranged from $2.42 x 10^{-4}$ to $2.78 x 10^{-4}$ m^2/s and increased with increase in temperature as shown in the table. The thermal diffusivities obtained at 50 and 60 ^{o} C were not significantly different but sample at 70 ^{o} C did at $p<0.05$. It is observed that increasing temperature had a corresponding increase in thermal diffusivity of the plantain studied. Ikegwu and Ekwu (2009) studied the thermal diffusivity in the temperature range of 50 to 70^o C varied from $1.15x10^{-7}$ to $1.62 \text{ x } 10^{-7} m^2 s^{-1}$. This is because thermal diffusivity relates the ability to store heat. Therefore speed of heat diffusion through a material is also relevant information in processing time prediction model. The model equation of Choi and Okos (1986) was used to calculate the specific heat capacity of the cultivars in order to determine the effect of temperature on specific heat capacity. The specific heat capacity values of plantain were decreased with increase in temperature as shown in Table 6. The specific heat capacity obtained ranged from ranged from 1.68 to 1.76 kJ/kgK which is greater than those values reported by Ikegwu and Ekwu (2009) which reported the specific heat capacity of plantain range from 0.077 to 0.023kJ kg^{-1}.

Effect of temperature on drying rate and moisture ratio

It is shown in Figure 1 that the sample exhibited a falling rate pattern. This is true because most agricultural products often exhibit falling rate period as reported by Ajala *et al.,* (2021); Velic *et al.,* (2007). During the falling rate period, drying occurred which mainly controlled by internal factor of diffusion mechanism in the chips as reported by Ajala and Abubakar, (2018); Ramaswamy and Marcotte, (2006) unlike constant rate period which could be controlled by external condition such as temperature, air humidity and air velocity. At this stage, there was no resistance to mass transfer as reported by (Ajala *et al.,* 2012, Gupta *et al.,* 2002).

The effect of temperatures on the drying characteristics of the sample is shown in Figure 1. It was discovered that drying rate was faster at 70 ^{o} C than 60 ^{o} C and 50 ^{o} C because, iinitially, drying rates were highest when moisture contents were higher, after which the drying rate decreased steadily with decreased moisture contents. This trend could be due to the removal of free moisture near the surface of the plantain slices at the early stages of drying. Drying rate is a function of temperature and time, and that more moisture was removed due to the low internal resistance of moisture at the beginning of the drying. As drying increased more energy was required to break the molecular bond of the moisture and since constant energy was supplied it took a longer time to break therefore drying rate decreased as moisture content decreased. As expected the increase in drying temperature resulted in a significant increase in drying rate. In similar but separate studies, Ajala, (2020) and Barre *et al.,* (2001) reported that drying rate values are dependent upon drying temperature during the drying this presupposes that the moisture holding capacity of heated air increases with increasing temperature. This observation was also reported by Ajala and Abubakar (2018) and Bellagha *et al.,* (2002). Also, this is because moisture migrates faster to the surrounding at higher temperature. This same observation was well reported in literature (Ajala *et al*. 2019 and Guine *et al.,* 2009).

Determination of activation energy

Activation energy in drying is the minimum energy that would be required to effect drying operation in food materials and it varies from product to another (Ajala *et al.*, 2021). In this study, the activation energy was found to be lower than that of banana (51.21kJ/mole) as reported by Islam *et al.* (2012), Candaba banana peels (64.9 kJ/mole) by Oni *et al.*, (2021) but higher than that for Oyster mushroom **(**19.825kJ/mol**)** by Ajala *et al*. (2021), potato (32.24 KJ/mole) by Islam, (2000) and grape seeds (30.45 KJ/mole) by Roberts *et al.*, (2008). The differences in activation energy values can be attributed to the differences in chemical composition and cellular structure.

Conclusion

Temperature played an important factor in removing moisture in the samples; at higher temperature of 70^{o}C, samples dried faster than at 60 ^{o} C and 50 ^{o} C. The effective moisture diffusivity of the sample was within the range of agricultural produce ((10^{-7} to 10^{-12}) and it increased as temperature increased. Fick's law of diffusion for thin layer drying was useful to model drying characteristics of plantain chips in tunnel dryer and page model best described the drying behaviour of the plantain compared to other models. Thermal properties were well dependent on drying temperature as thermal conductivity, specific heat capacity and density decreased with increase in temperature while thermal diffusivity increased with increase in temperature.

REFERENCES

Adepoju, OT, Sunday BE and Folarami OA (2012). Nutrient composition and contributions of plantain, (*Musa paradisiaca*) products to dietary diversity of Nigerian consumers. *African Journal of. Biotechnology* **11**(71) 13601-13605.

Agoyero BO, Akpiroroh OO, Osaweren OR and Owabor CN (2011). The effect of various drying methods on the nutritional composition of *Musa paradisiaca, Dioscorea rotundata* and *Colocasia esculenta*. *Asian Journal of Biochemistry,* **6** 458-464.

Ajala AS, Aboiye AO, Popoola JO, Adeyanju JA (2012). Drying characteristics and mathematical modelling of cassava chips. *Chemical and Process Engineering Research*, **4** 1-9.

Ajala AS and Idowu TO (2016). Investigation on the Quality of Fermented White Yam Flour (Elubo) at Different Drying Temperatures. *Canadian Journal of Agriculture and Crops*, **1**(1) 1-10.

Ajala AS and Abubakar MA (2018). Study of Drying Kinetics and Quality Attributes of Fermented Corn Grains as Affected by Drying Temperatures and Velocities. *Journal of Nutritional Health & Food Engineering*, **8**(2) 205–212.

Ajala AS, Olaniyan SA, Fasonyin OT and Adeoye AO (2019). Production and optimization of citric acids from cassava peels using *Aspergillus Niger*. *World Journal of Engineering Research and Technology,* **5**(2) 187-199.

Ajala AS (2020). Optimization of the drying process of cassava chips using response surface methodology. *American Journal of Food Technology*, **15** 11-21

Ajala AS, Ogunsola AD and Akanbi TA (2021). Evaluation of Drying Kinetics and Activation Energy of Oyster Mushroom (*Pleurotus ostreatus*), *LAUTECH Journal of Civil and Environmental Studies*, **6**(1) 135-143

AOAC (2012). Official Methods of Analysis (16th edn). *Association of Official Analytical Chemists*. Virginia, USA.

Balasooriya, BMC, Champa WAH and Palipana KB (2006). Effect of hydrocooling on prolonging shelf life of banana; variety ambul. *Sri lankan Journal of Agriculture Science*, **43** 66-81.

Barre HJ, Baughman GR and Hamdy MY (2001). Application of the Logarithmic Model to Cross-flow Deep-bed Grain drying. *Transactions of the ASAE*. **14** (6) 1061-1064.

Bellagha S, Amami E, Fahart H and Kechaou N (2002). Drying kinetics and characteristics drying curve of lightly salted sardine. *Proceeding of the 13th international drying symposium*. Volume C, p 1583.

Bhuchiss T, Sirichai T and Wathanyoo R (2008). Drying kinetics of natural-rubber slab in a convective hot-air dryer. *Technology and Innovation for Sustainable Development Conference journal*, **1** 1-6.

Choi Y, Okos M (1986). Thermal properties of Liquid Foods – Review. In Physical and Chemical Properties of Food, Okos MR (ed). St. Joseph MI: *American Society of Agricultural Engineers*.

Ditchfield C, Tadini CC, Singh RK and Toledo RT 2005. Experimental Determination of Heat Transfer Coefficient in Banana Puree. *Eurotherm Seminar 77- Heat and Mass Transfer in Food Processing*, June 20-22, Parma, Italy.

Doymaz I (2004) Convective air drying characteristics of thin layer carrots. *Journal of Food Engineering*. **61**(3), 359-364.

Doymaz and Akgun (2005). Drying kinetics of white mulberry. *Journal of Food Engineering* **61**, 341346.

Eklou SA, MS Ines, N Frances, S Moussa, OA Ayoni, S Kayode and TO Daniel (2006). Comparative study of drying methods on seed quality of interspecies NEGERA rice varieties (Oriza glaberimax, Orisa sativa) their parents. African. *Journal of Biotechnology*, **5** 1618-1624.

Emperatriz PD, M Ronald P Elevina and S Mily (2008). Production and characterization of unripe plant zain (*Musa paradisiaca* L.) flours Inter science environment. *Blackwell Science Ltd* **19**, 356-361.

FAO, (2005), (Food and Agriculture Organization). *Food and Agriculture indicators ESSA October* 2005.

Goyal RK, Kingsley ARP, Manikantan MR and Ilyas SM (2007). Mathematical modeling of thin layer drying kinetics of plum in a tunnel dryer. *Journal of Food Engineering* **79**(1) 176-180.

Guine R, Lopes P, Joao BM and Ferreira DMS (2009). Effect of ripening stage on drying kinetics and properties of S. Bartolomeu pears. *International Journalof Academic Research*,**1(**1) 3.

Gupta P Ahmed J, Shivhare US and Raghavan GSV (2002). Drying characteristics of red chilli. *Drying Technology* **20** 1975 – 1978.

Hill KA and Pyke N (2009). Influence of commercial drying on maize grain attributes – 1997. *Foundation for arable research* (far) arable update no. 10.

Ikegwu OJ and Ekwu FC (2009). Thermal and physical properties of some tropical fruits and their juices in Nigeria. *Journal of Food Technology*. **7**(2) 38-42.

Islam, M. N. (2000). Kinetic analysis of air drying of potato: traditional and improved methods. *Journal of Agricultural Engineering, Institute of Engineers Bangladesh*, **12** 3-11.

Kingly RP, Goyal RK, Manikantan MR and Ilyas SM (2007). Effect of pretreatment and drying air temperature on drying behaviour of peach slice. *International Journal of Food Science and Technology*, **4** 65-69.

Morris AA, Barnett and O Burrows (2004). Effect of processing on the nutrient content of foods. **37** 160-164.

Nwabanne JT (2009). Drying characteristics and engineering properties of fermented ground cassava. *African Journal Biotechnology* **8**(5) 873-876.

Oni OK, Ajala AS and Oloye AO (2021). Effect of Different Drying Methods on the Drying Kinetics of Fermented Cardaba Banana Peels. FUOYE *Journal of Engineering and Technology (FUOYEJET)*, **6** (2) 5-9,

Perussello CA, VC Mariani and LA Mendez 2010. Development of a linear heat source probe and determination of Banana thermal conductivity. *International Journal of Food Engineering*, **6**(5) Article 12.

Ramaswamy H and Marcotte M (2006). Food Processing - Principles and Applications. London: Taylor and Francis Group.

Roberts JS, Kidd DR and Padilla-Zakour O (2008). Drying kinetics of grape seeds. *Journal of Food Engineering*, **89** 460–465.

Salawu SO, Shaibu R, Afolabi AA, Boligo AA and Athayde ML (2015). Nutraceutical potential and sensory acceptability of unripe plantain-millet Composite Flour Blends. *Food Science and Quality Management*, **39** 84-97.

Sanjuán N, Lozano M, Pablo GP and Antonio M (2003). Dehydration kinetics of red pepper *Capsicum annuum* L var Jaranda). *Journal of the Science of Food and Agriculture* **83**(7) 697 – 701.

Savage GP, Dutta PC and Rodriguez-Estrada MT (2002). Cholesterol oxides: Their occurrence and methods to prevent their generation in foods. *Asian Practical Journal of Clinical Nutrition*, **11** 72-78.

SRID –MOFA (2006). Statistic, Research and Information Directorate, Ministry of Food.

Sweat VE (1995). Thermal properties of foods, Macel Dekker Inc., New York.

Togrul IT, Pehlivan D (2004). Modeling of thin layer drying of some fruits under open-air sun drying process. Journal of Food Engineering **65**, 413–425.

Velić D, Bilić M, Tomas S, Planinić M, Bucić-Kojić A and Aladić K (2007). Study of the Drying Kinetics of "Granny Smith" Apple in Tray Drier, *Agriculturae Conspectus Scientificus* **72**(4) 326.

Yusuf KO, Ajeigbe OM, Oyebo AT, Aderinboye RY, Adelusi OO and Onwuka CFI (2017). Nutrients and anti-nutrients content of some crop by-products and residues for ruminant feeding in Nigeria. *Journal of Animal Production Research*, **29**(1) 249-262.

Nomenclature

a	Drying constant in the model
b	Drying constant in the model
c	Drying constant in the model
j	Drying constant in the model
k	Drying constant in the model
l	half of the thickness of the sample (m^2)
M_0	initial moisture content of the sample (g water/g solid)
M_i	instantaneous moisture content (g water /g solid)
M_e	equilibrium moisture content (g water/g solid)
MBE	mean bias error
MR	moisture ratio
MR_{exp}	experimental moisture ratio
MR_{pre}	predicted moisture ratio
n	Drying constant in the model
N	number of observation
RMSE	root mean square error
R^2	coefficient of determination
t	drying time (hr)
χ^2	reduced chi square
z	number of constant in the models