Drying kinetics of unripe plantain chips using charcoal fuelled cabinet dryer

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Abstract: This study presents the thin layer drying behavior of unripe plantain slices (Musa paradisiaca) in a developed biomass cabinet dryer. The developed dryer provided an environment with an optimum operating temperature between 50℃ -70℃ meant for drying agricultural materials. The use of thin layer drying mechanisms and equations contribute to better understanding of drying food materials. The thin layer drying behaviour of agricultural products was identified based on the mathematical models which describe the heat and mass transfer phenomena of the products. In order to select a suitable drying model, fourteen different thin layer drying models were fitted to experimental data. Fick's second law was used to calculate the moisture diffusivity with some simplifications. The results were compared for their goodness of fit in terms of correlation coefficient (R^2), reduced chi square (χ^2), root mean square error (RMSE), and mean bias error (MBE). Effective moisture diffusivity values of unripe plantain slices during drying were -56.8 x 10-1, -2.60 x 10-1 and -6.84 x 10-1 m2/s for charcoal at 5, 10 and 15 mm thicknesses. Midilli and Kucuk, Modified Henderson and Wangh and Singh models were most suitable to describe the drying behavior of unripe plantain at 5, 10 and 15 mm thicknesses respectively when dried with charcoal and there were good agreements between the experimental and predicted variables.

Keywords: thin layer, mathematical modeling, diffusion, drying, biomass fuel

1 Introduction

Plantain (*Musa paradisiaca*) is one of the most important tropical products and fruit of an herbaceous perennial plant which are highly prone to post harvest losses. This agricultural product has high moisture content at harvest and therefore cannot be preserved for more than some few days under ambient conditions of 20℃–25℃ (Chua, et al., 2001). Drying has always been of great importance for the preservation of food. Drying of fruits and vegetables involves simultaneous, coupled heat and mass transfer, under transient conditions (Diamante, et al., 2010). In most cases, drying involves the application of thermal energy, which causes water to evaporate into the vapour phase. The major objective of drying food products is the reduction of moisture content to a level which allows safe storage over an extended period (Doymaz, 2004).

The introduction of dryers capable of operating on biomass fuel in developing countries will reduce post-harvest losses and improve the quality of dried product significantly when compared to bottlenecks experienced inconventionalmethods of drying using electricity. To analyze the drying behaviour of a food product, it is essential to study the drying kinetics of the food. According to (ASAE, 2001), thin layer drying refers to a layer of material exposed fully to an airstream during drying. There is a wide range of thin layer drying models, which have found application because of their ease of use. Thin layer drying equations are often empirical to describe drying phenomena in a unified manner regardless of the controlling mechanism (Kadam, et al., 2010). Drying of many fruits and other agricultural products have been successfully predicted by Sereno and Medeiros, (1990), Muthukumarappan and Gunasekaran, (1994), Ratti and Mujumdar, (1997), Afzal and Abe,

(1998), Agar, et al., (1999), Iguaz, et al., (2003), Baini and Langrish, (2007) but there is no literature specifically on the mathematical modeling of unripe plantain slices using charcoal fuels.

2 Materials and methods

2.1 Material preparation and drying operation

Fresh unripe plantains (*Musa paradisiaca)* were purchased fromIlara-Mokin main market in Ondo State, Nigeria. The unripe plantains were peeled and sliced with FUTA slicer into 5, 10 and 15 mm thicknesses. The slices were measured with vernier caliper for thickness accuracy.

A laboratory scale biomass fuelled cabinet hot-air dryer of the static-tray type developed at the "Agricultural Engineering Machinery Workshop" of Federal University of Technology, Akure, Nigeria was used for this study, (see Figure 1). The main parts of the dryer system consist of three functional subsystems namely: the drying chamber (fitted with temperature sensor), combustion chamber (designed with slit opening to regulate the rate of combustion), and chimney (through which the smoke escapes).

Figure1Front view of the charcoal fuelled cabinet dryer

Before loading the dryer, it was heated for eight minutes in order to achieve a desirable steady state temperature condition of 60℃ (Rayaguru and Routray, 2012). Moisture content of samples before drying was determined according to the AOAC (1990). Approximately 200 g sample of unripe plantains at each thickness were loaded in a thin layer in the developed biomass fuelled cabinet dryer (Tunde-Akintunde and Afon, 2009).

The samples were being removed at regular intervals of 30 minutes and were weighed, using a precision weighing balance model EK 410i with an accuracy of 0.1 g until three consecutive weights were constant, indicating equilibrium condition. Drying experiments were conducted in triplicate and average values were recorded.

2.2 Theoretical considerations

The moisture ratio (*MR*) of unripe plantain slices during drying experiments was calculated using the following Equation 1:

$$MR = \frac{M-M_e}{M_o-M_e} \quad\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad (1)$$

Where,*M*, *Mo*, and *Me* are moisture content at any drying time, initial and equilibrium moisture content (kg water/kg dry matter), respectively. The values of *Me*are relatively small compared to those of *M* or *Mo*, hence the error involved in the simplification is negligible (Aghbashloet al., 2008), hence moisture ratio was calculated as Equation 2:

$$MR = \frac{M}{M_o} \quad\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad (2)$$

The goodness of fit was determined using three parameters: coefficient of determination (R^2), reduced chi-square (χ^2) and root mean square error (*RMSE*) using Equation 3, Equation 4, Equation 5 and Equation 6, respectively (Togrul and Pehlivan, 2002). Multiple regression analysis was performed using Sigma plot computer software program.

$$R^2 = \frac{\sum_{i=1}^{N}(MR_i - MR_{pre,i})*(MR_i - MR_{exp,i})}{[[\sum_{i=1}^{N}(MR_i - MR_{pre,i})]*[\sum_{i=1}^{N}(MR_i - MR_{pre,i})]]^{1/2}} \quad (3)$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{N-n} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (4)$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(MR_{\text{pre,i}} - MR_{exp,i})\right]\ldots\ldots\ldots\ldots\ (5)$$

$$MBE = \frac{1}{N}\sum_{i=1}^{N}(MR_{pre,i} - MR_{exp,i})\ldots\ldots\ldots\ldots\ldots\ldots\ (6)$$

In the above Equations $MR_{pre,i}$ is the ith predicted moisture ratio, $MR_{exp,i}$ is the ith experimental moisture ratio, N is number of observations and n is number of constants. The higher values for R^2 and lower values for and $RMSE$ are chosen as the criteria for goodness of fit (Demir, et al., 2004). See Table 1.

Table 1 Thin layer mathematical models used to describe the drying kinetics of unripe plantain slices using biomass fuels

No	Model Name	Model Equation[1]	Reference
1	Lewis	MR = exp(-kt)	Demiret al. (2007)
2	Page	MR = exp(-kt^n)	Flores et al. (2012)
3	Modified Page	MR = exp[-(kt)^n]	Demiret al. (2007)
4	Henderson &Pabis	MR = aexp(-kt)	Flores et al. (2012) , Radhikaet al. (2011)
5	Logarithmic	MR = aexp(-kt)+c	Shen et al.(2011)
6	Two Term	MR = aexp(-k$_1$t)+bexp(-k$_2$t)	Flores et al.,(2012)
7	Two Term Exponential	MR = aexp(-kt)+(1-a)exp(-kat)	Shen et al.(2011), Evin, (2011)
8	Wang & Singh	MR = 1+at+bt^2	Flores et al. (2012) ,Radhika et al.(2011)
9	Approximation of diffusion	MR = aexp(-kt)+(1-a)exp(-kbt)	Flores et al. (2012)
10	. Verma*et al.*	MR = aexp(-kt)+(1-a)exp(-gt)	Verma et al.(1985)
11	Modified Henderson &Pabis	MR=aexp(-kt)+bexp(-gt)+ cexp(-ht)	Evin (2011), Meziane (2011)
12	Simplified Fick''s Diffusion	MR = aexp[-c(t/L^2)]	Diamente and Munro, (1991)
13	Modified Page II	MR = exp[-k(t/L^2)^n]	Diamente and Munro, (1993)
14	Midilli&Kucuk	MR = aexp(-ktn)+bt	Midilli et al. (2002)

Note: [1] Where $MR = (M - M_e)/(M_o - M_e)$, moisture ratio (dimensionless); a, b, c, g, h, k, k_1, k_2 and n = drying constants; t = drying time (h).

2.3 Estimation of effective moisture diffusivity

Fick's second law of diffusion equation for objects with slab geometry is used for calculation of effective moisture diffusivity. The equation can be used to model the drying behavior of fruits and vegetables. The Equation 7 is expressed by (Maskan, et al., 2002):

$$MR = \frac{8}{\pi 2}\exp\frac{-\pi Defft}{4L2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (7)$$

Where, MR is the dimensionless moisture ratio, D_{eff} is the effective moisture diffusivity in m^2/s, t is the time of drying in seconds and L is half of the slab thickness in metres. The diffusion coefficient was typically calculated by plotting experimental drying data in terms of ln(MR) versus drying time. The effective diffusivity, D_{eff} can be calculated using method of slopes (Maskan, et al. 2002; Doymaz, 2004).

The effective diffusivity of the unripe plantain slices was calculated by Equation 8 thus,

$$\text{Slope K} = \frac{Deff\pi 2}{4L2} \ldots\ldots\ldots\ldots\ldots\ldots\ (8)$$

3 Results and discussion

3.1 Drying characteristics of plantain slices with charcoal fuels

The drying of plantain slices exhibited the behavior of moisture desorption characteristics when charcoal fuels generated hot air for drying the samples. There was an initial high moisture removal followed by slow moisture removal in the latter stages of drying (Figure 2). Irrespective of the plantain slice thicknesses, the entire drying process for the samples occurred in the range of falling rate period. These curves did not exhibit a constant rate period, which agrees with the results of other studies on basil, banana and plantain (Rocha et al., 1993; Johnson,

et al., 1998; Maskan, 2000; Saeed, et al., 2006; Falade and Abbo, 2007; Kaya, et al., 2007; Nguyen and Price, 2007; Singh, et al., 2008). This means that diffusion is the dominant physical mechanism governing moisture movement in the material which is dependent on the moisture content of the samples (Akpinar, et al., 2003; Doymaz, 2007b; Prachayawarakorn, et al., 2008).
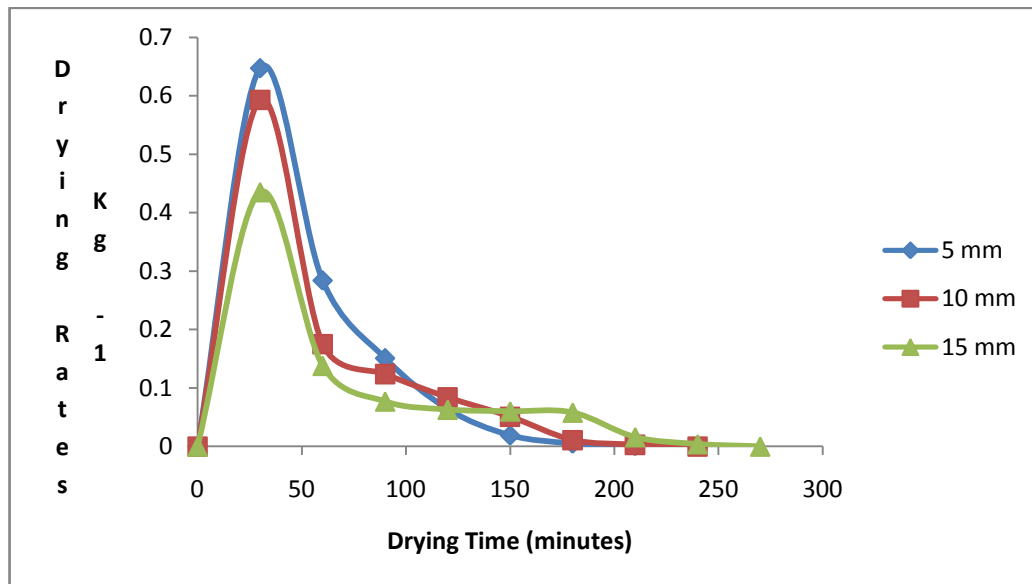

Figure 2 Relationship between drying time and drying rates of plantain slices at 5, 10 and 15 mm thicknesses dried with Charcoal fuel

3.2 Mathematical modelling of drying curves

Table 2, Table 3 and Table 4 show the results of fitting the experimental data to the thin layer drying models listed in Table 1. The criterion for selection of the best model to describe the thin layer drying behavior of plantain slices was based on the highest correlation coefficient (R^2), and least of the reduced chi-square (χ^2), the root mean square error (RMSE) and the mean bias error (MBE) values (Sarasvadia, et al., 1999; Togrul and Pehlivan, 2003; Erenturk, et al., 2004; Demir, et al., 2004; Goyal, et al., 2006).

Table 2 Results of statistical analysis of the modeling of moisture ratio and drying time for 5mm thickness plantain slicesdried with charcoal fuelled hot air

Model Name	Model Constants	R^2	RMSE	MBE	χ^2
Lewis	b= 0.0125	0.9844	0.11298	-0.0728	0.00159
Logarithmic	a=0.9648, b=0.0150, c=0.0606	0.9900	0.05226	6.476E-17	0.00136
Two-Term	a=0.9648, c=0.0606, b_0=0.0150, b_1=1.289E-012	0.9900	0.04526	4.857E-17	0.00163
Two-Term Exponential	a=0.5264, b=0.0172	0.9858	0.07606	-0.0258	0.00165
Midilli and Kucuk	a=0.9980, b=0.0037, n=1.3180, d=0.0005	0.9995	0.00995	5E-05	0.00231
Page Model	b=0.0133, n=0.9858	0.9844	0.07972	-0.0345	0.00165
Modified Page	b=0.0125, n=0.9858	0.9844	0.07972	-0.0345	0.00165
Henderson and Pabis	a=1.0083, b=0.0126	0.9845	0.07958	-0.0328	0.00165
Approximation of Diffusion	a=0.9443, b=0.0144, d=6.0931E-011	0.9890	0.05458	-0.009833	0.00148
Wangh and Singh	a=-0.0100, b=2.694E-005	0.9919	0.057415	0.01205	0.00094
Verma*et al*	a=0.0557, b=9.9588E-013, h=0.0144	0.9890	0.05458	-0.009833	0.00148
Modified Henderson	a=-0.1769, b=0.7806, c=0.0060, g=0.0161, h= -0.0118, d=1.1708	0.9987	0.01351	0.0002167	0.00036
Simplified Fick's Diffusion	a=1.0083, c=0.3146, L=5.000	0.9845	0.06498	-0.02187	0.00211
Modified Page ll	a=1.0123, L=5.000, k=0.3267, n=0.9738	0.9846	0.05602	-0.0137	0.00251

Table 3 Results of statistical analysis of the modeling of moisture ratio and drying time for 10mm thickness plantain slices dried with charcoal fuelled hot air

Model Name	Model Constants	R^2	RMSE	MBE	$\chi 2$
Lewis	b=0.0096	0.9900	0.08703	0.018	0.00094
Logarithmic	a=0.9846, b=0.0103, c=0.0267	0.9905	0.04901	3.7007E-17	0.00120
Two-Term	a=0.0267, c=0.9846, b_0=4.5361E-012, b_1=0.0103	0.9905	0.04245	2.77556E-17	0.00144
Two-Term Exponential	a=0.9888, b=0.0037, n=1.2356, d=0.0004	0.9943	0.06146	-0.00965	0.00107
Midilli and Kucuk	b=0.0086, n=1.0225	0.9902	1.51733	1.858325	0.00086
Page Model	b= 0.0096, n=1.0225	0.9902	0.06114	-0.0093	0.00086
Modified Page	b=0.0096, n=1.0225	0.9902	0.06114	-0.0093	0.00106
Henderson and Pabis	a=1.0055, b=0.0097	0.9901	0.06139	-0.00595	0.00106
Approximation of Diffusion	a=-0.0384, b=0.0454, d=0.2190	0.9904	0.04943	-0.0058	0.00107
Wangh and Singh	a=-0.0082, b=1.9359E-005	0.9974	0.03161	-0.00355	0.000285
Verma*et al*	a=-0.0384, b=0.0454, g=0.0099	0.9904	0.04943	-0.0058	0.00122
Modified Henderson	a=2.9306, b=0.0032, c=0.2232, g=6.4468E-016, h=-0.0060, d=-2.1609	0.9975	0.01789	1.6667E-05	0.00064
Simplified Fick"s Diffusion	a=1.0055, c=0.9654, L=10.000	0.9901	0.05012	-0.0039667	0.00125
Modified Page ll	a=1.0016, L=10.000, k=0.9591, n=1.0203	0.9902	0.04320	-0.004225	0.00149

Table 4 Results of statistical analysis of the modeling of moisture ratio and drying time for 15mm thickness plantain slices dried with charcoal fuelled hot air

Model Name	Model Constants	R^2	RMSE	MBE	$\chi 2$
Lewis	b=0.007	0.9763	0.14128	-0.0055	0.00249
Logarithmic	a=1.2189, b=0.0050, c=-0.2142	0.9853	0.11126	-3.333E-05	0.00206
Two-Term	a=1.0800, c=-0.0800, b_0=0.0076, b_1=0.9258	0.9810	0.12647	0.006775	0.00319
Two-Term Exponential	a=1.7453, b=0.0098	0.9872	0.10388	0.0114	0.00154
Midilli and Kucuk	a=0.9777, b=0.0017, n=1.2856, d= 4.795,E-005	0.9873	0.10356	0.0003	0.00214
Page Model	b=0.0024, n=1.2129	0.9867	0.10576	0.012	0.00159
Modified Page	b=0.0070, n=1.2129	0.9867	0.10576	0.012	0.00159
Henderson and Pabis	a=1.0305, b=0.0073	0.9782	0.13570	0.0194	0.00263
Approximation of Diffusion	a=894.7445, b=0.0031, d=0.9990	0.9857	0.10962	-0.0021	0.00200
Wangh and Singh	a=-0.0057, b=8.872E-006	0.9889	0.09662	-0.00285	0.00133
Verma*et al*	a=-0.0800, b=0.9064, g=0.0076	0.9810	0.12647	0.009033	0.00266
Modified Henderson	a=-0.0800, b=102.041, c=8.114E-016, g=0.0076, h=1119.293, n=1.0800	0.9810	0.12647	0.004517	0.00533
Simplified Fick"s Diffusion	a=1.0305, c=1.6315, L=15.000	0.9782	0.13570	0.012933	0.00306
Modified Page ll	a=0.9800, L=15.000, k=1.7264, n=1.2573	0.9872	0.10370	-5E-05	0.00215

The results for 5 mm thickness are shown in Table 2. R^2 values ranged from 0.9844 - 0.9919. The R^2 values for Midilli and Kucuk model are higher than that from the other thirteen models, χ^2 values varied between 9.4×10^{-4} - 3.6×10^{-3}, RMSE values varied from 0.00995 - 0.11298 while MBE values varied -0.0728 - 0.0345. For the fourteen examined models in Table 2, the results for the overall best fits gave $R^2 = 0.9995$, $\chi^2 = 0.00231$, RMSE = 0.00995 and MBE = 5E-05 values for Midilli and Kucuk. This indicates that Midilli and Kucuk model gave a better correlation between the moisture ratio and drying time.

The results for 10 mm thickness are shown in Table 3 had R^2 values ranged from 0.9900 - 0.9974, χ^2 varied from 0.00064 - 0.00144, RMSE varied from 0.01789 - 1.51733 and MBE varied from -0.018 - 1.858325. For all the models in Table 3, the results for the overall best fits gave $R^2 = 0.9975$, $\chi^2 = 0.00064$, RMSE = 0.01789 and MBE = 1.67E-05 values for the thin layer drying conditions, the Modified Henderson drying model gave the highest R^2 and lowest χ^2, RMSE and MBE values

The results for 15 mm thickness are shown in Table 4; R^2 values ranged from 0.9763 - 0.9889, χ^2 varied from

0.00133 - 0.00533, RMSE varied from 0.09662 - 0.14128 and MBE varied from -0.0055 - 0.0194. For all the models in Table 4, the results for the overall best fits gave $R^2 = 0.9889$, $\chi^2 = 0.00133$, RMSE = 0.00133 and MBE = 0.00285 values for the thin layer drying conditions. These satisfied Wangh and Singh drying model as it gave the highest R^2 and lowest χ^2, RMSE and MBE values. This indicates that Wangh and Singh drying model gave a better correlation between the moisture ratio and drying time.

3.3 Validation of the established model

Validation of the established model was made by plotting the experimental and predicted moisture ratio values with drying time as shown in Figures 3, 4 and 5. There was a good agreement between the experimental and predicted variables.
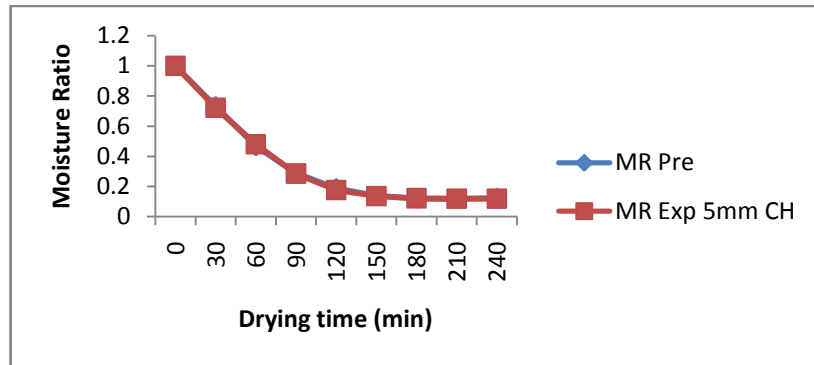

Figure 3 Comparison of experimental and predicted moisture ratio values by Midilli and Kucuk model for 5 mm plantain thickness
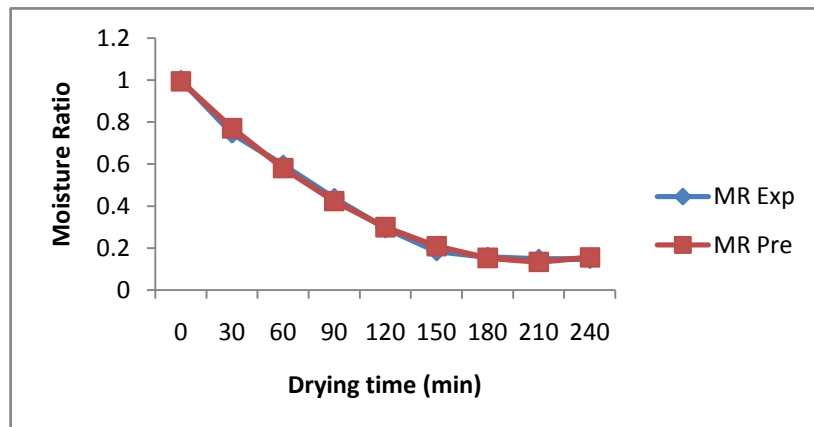

Figure 4 Comparison of experimental and predicted moisture ratio values by Modified Henderson model for 10 mm plantain thickness
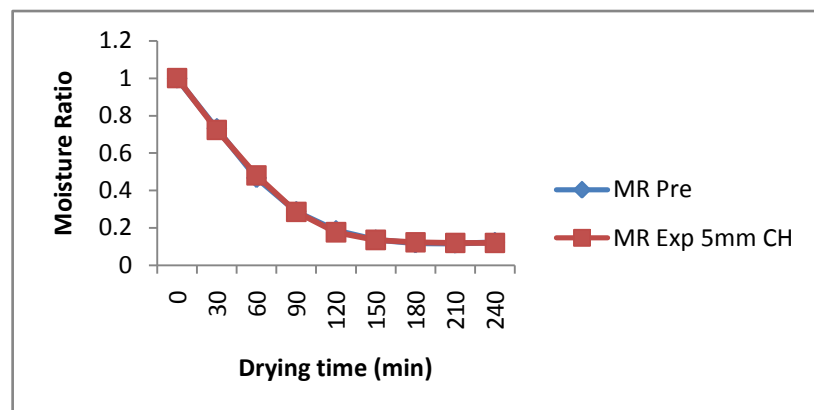

Figure 5 Comparison of experimental and predicted moisture ratio values by Wangh and Singh model for 15 mm plantain thickness

3.4 Effective diffusion coefficient of unripe plantain slices (m^2/s)

The drying data of unripe plantain slices were analyzed to obtain the values of the effective diffusivity during the falling drying rate phase. Effective moisture diffusivity was calculated using slopes derived from In MR against drying time (s). The calculated effective diffusion coefficient of unripe plantain slices dried with charcoal fuel is shown in Table 5

Table 5 Effective moisture diffusivity obtained for charcoal fuelled dried unripe plantain slices at 5, 10 and 15 mm thicknesses

	Effective moisture diffusivity (m^2/s) x 10^{-1}		
	5 mm	**10 mm**	**15 mm**
CharcoalFuelled-56.8	-2.60	-6.84	

There is generally increase in moisture diffusion with increasing drying time from -56.8 x 10^{-1} to -2.60 x 10^{-1} m^2/s for 5 and 10 mm thicknesses respectively, but at 15 mm thickness the moisture diffusion reduced to -6.84 x 10^{-1} m^2/s.

This was expected since water loss increased with increasing temperature and time.Azoubel and Murr (2002); Alakaliet al. (2006) observed similar trends in cherry tomatoes and mango slabs respectively. According to the authors, the kinetic energy of molecules of water increased at high temperatures resulting in increased rate of diffusion. The inconsistency in the trend of moisture increase in diffusivity in this study might be as a result of the biomass cabinet dryer not operating on constant air velocity but on the velocity of the primary surrounding air.

Similar result have been obtained for other agricultural crops like organic tomatoes: 2.56×10^{-9}, 4.28×10^{-9} and 4.29×10^{-9} - 6.28×10^{-9} m^2/s (Sacilik, et al, 2006); yam slices: 7.62×10^{-8} - 9.06×10^{-8} m^2/s (Sobukola,et al, 2008); okra: 1.125×10^{-9}, -9.93×10^{-9} m^2/s and 1.165×10^{-8} - 7.13×10^{-9} m^2/s for treated and untreated

samples respectively (Sobukola, 2009). Thus the diffusivity values obtained from the experimental data fall within the (10^{-11}-10^{-6} m^2/s) range reported for most food products (Doymaz, 2007a; Tunde-Akintunde and Afon, 2009).

4 Conclusions

Drying experiment conducted on the thin- layer drying behavior of unripe plantain slices at 5, 10 and 15 mm thicknesses were tested with fourteen thin-layer model equations. The results of the study showed thatMidilli and Kucuk, Modified Henderson and Wangh and Singh models best described the drying characteristic of plantain pulp at 5, 10 and 15 mm thicknesses respectively when charcoal was used as biomass fuel for drying. Validations of the established models showed that there were good agreements between the experimental and predicted variables. Effective moisture diffusivity values of unripe plantain slices during drying were -56.8 x 10^{-1}, -2.60 x 10^{-1} and -6.84 x 10^{-1} m^2/s for charcoal fuel which is in the suitable range for similar products.

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