Drying kinetics of unripe plantain chips using charcoal fuelled cabinet dryer

Famurewa J. A. V.*, Adejumo A. O.

(*Department of Food Science and Technology, Federal University of Technology, Akure , Nigeria*)

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 (R2), reduced chi square (χ2), 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

Citation: Famurewa J. A. V., Adejumo A. O. 2015. Drying kinetics of unripe plantain chips using charcoal fuelled cabinet dryer. AgricEngInt: CIGR Journal, 17(1): 227-235.

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,

Received date: 2014-10-17 **Accepted date:** 2015-02-19
***Corresponding author:Famurewa J. A. V.,** Department of Food Science and Technology, Federal University of Technology jav_murewa@yahoo.com

(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:

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

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:

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

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.

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

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

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

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

In the above Equations *MRpre,i*is the *i*th predicted moisture ratio, *MRexp,i*is the *i*th 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_1t)+bexp(-k_2t)	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):

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

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,

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

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).

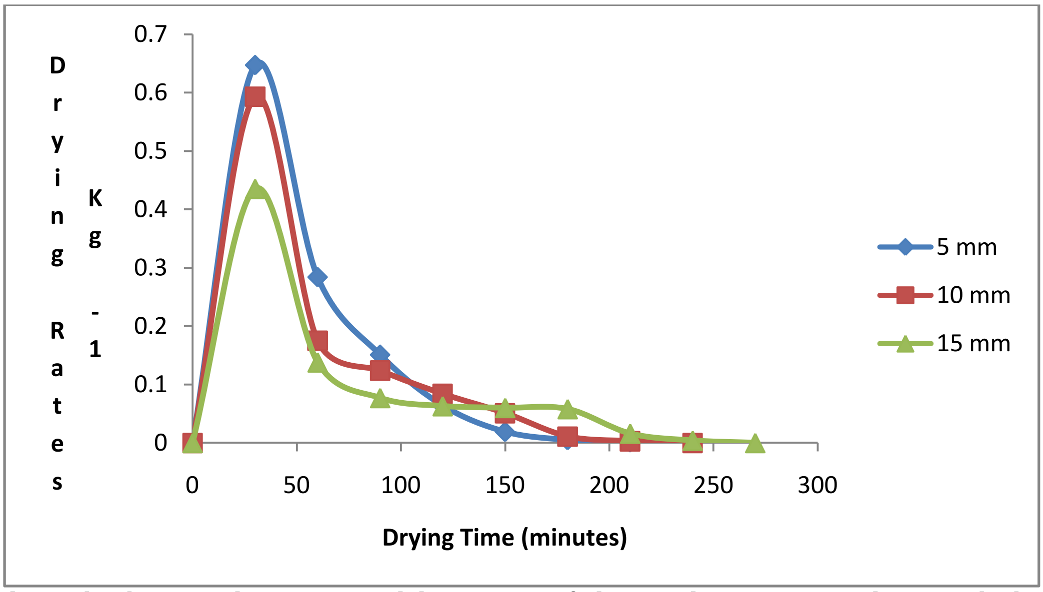

Figure 2 Relationship between drying time and drying rates of plantain slices at 5, 10 and 15 mm thicknesses dried with Charcoal fuel

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	χ2
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	χ2
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	χ2
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 x 10^{-4} - 3.6 x 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, χ^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, χ^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.

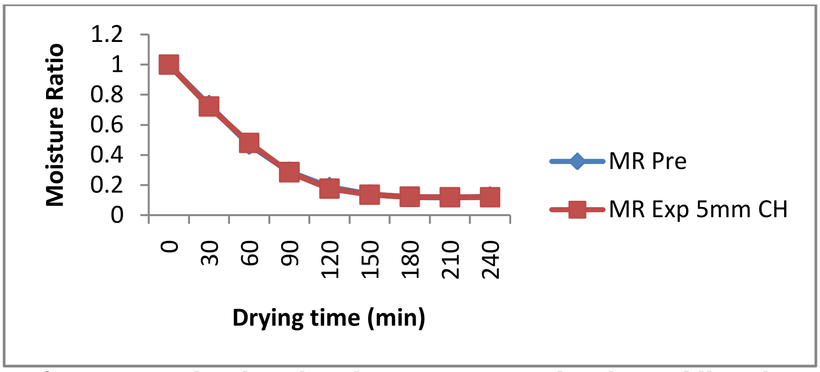

Figure 3 Comparison of experimental and predicted moisture ratio values by Midilli and Kucuk model for 5 mm plantain thickness

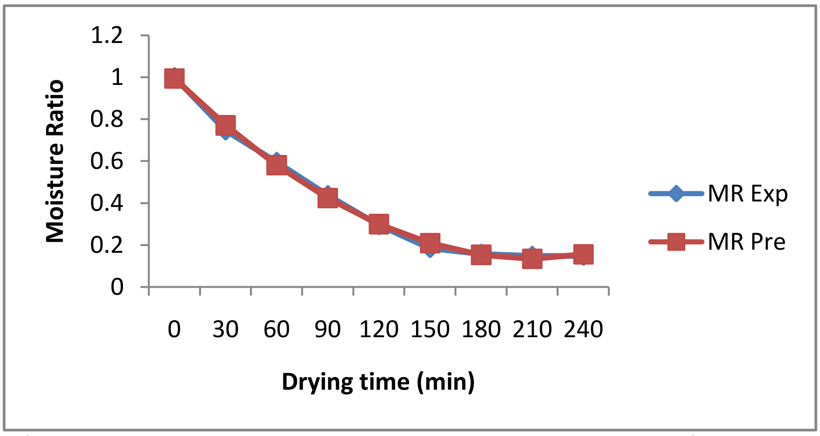

Figure 4 Comparison of experimental and predicted moisture ratio values by Modified Henderson model for 10 mm plantain thickness

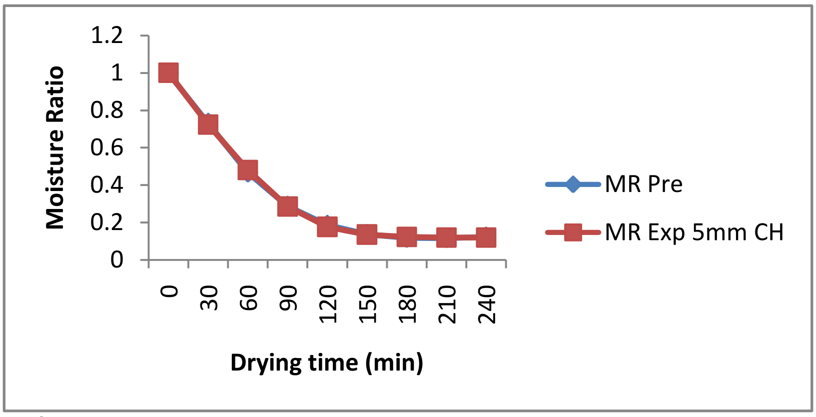

Figure 5 Comparison of experimental and predicted moisture ratio values by Wangh and Singh model for 15 mm plantain thickness

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.

References

Afzal, T. M. and T.Abe.1998. Diffusion in potato during infrared radiation drying. *Journal of Food Engineering*, 37(4): 353-365.

Agar, T. I., R Massantini, , B. Hess-Pierce,and A. A.Kader. 1999. Postharvest CO^2 and ethylene production and quality maintenance of fresh-cut kiwi fruit slices. *Journal of Food Science*, 64(3): 433- 440.

Aghbashlo, M, MH Kianmehr, and H Samimi-Akhljahani.2008. Influence of drying conditions on the effective Effective moisture diffusivity, energy of activation and energy consumption during the thin-layer drying of barberries fruit (Berberidaceae). *Energy Conversion and Management*, 49(10): 2865–2871.

Akpınar, E. K. and Y Bicer.2003. Modeling and experimental study on drying of apple slices in a convective cyclone dryer. *Journal of Food Process Engineering*, 26(6):515-541.

Akpinar, E., A.Midilli, and Y.Bicer.2003. Single layer drying behaviour of potato slices in a convective cyclone dryer and mathematical modelling. *Energy Conversion and Management*, 44(10):1689–1705.

Alakali, J. S., C. C Ariahu, and N. N.Mkpa.2006. Kinetics of osmotic dehydration of mango fruit slabs. *Journal of Food Processing and Preservation,* 30(5): 597- 607.

AOAC.1990. Official Methods of Analysis of the Association of Official Analytical Chemists, 15th ed., AOAC, Arlington, Virginia, USA

ASAE.2001. /ANSI S448 Jul (R2006). Thin layer drying of agricultural crops.Pp 621-624.

Azoubel, P. M and F. E. X.Murr.2002. Mathematical modeling of the osmotic dehydration of cherry tomatoes (*Lycopersicumesculentum*var. cerasitorme).*Ciencia e Technologia de Alimentos*.http://www.scielo.br/scielo.php?script=sci_arttext&pid=S0101-20612000000200017. Accessed in February 10th 2012

Baini, R. and T. A. GLangrish.2007. Choosing an appropriate drying model for intermittent and continuous drying of bananas. *Journal of Food Engineering*, 79 (1): 330-343.

Chua, K. J., A. S.Mujumdar, M. N. A.Hawlader, S. K.Chou,and J. C.Ho.2001. Batch drying of banana pieces—effect of stepwise change in drying air temperature on drying kinetics and product colour. *Food Research International,* 34(8):721–731.

Demir, V., T.Gunhan, A. K.Yagcioglu,andA.Degirmencioglu. 2004. Mathematical modeling and the determination of some quality parameters of air-dried bay leaves. *Bio systems Engineering*,88(3):325–335.

Demir, V., T.Gunhan, and A. K.Yagcioglu. 2007. Mathematical modeling of convection drying of green table olives.*Biosystems Engineering*,98(1): 47-53.

Diamante, LM and PA Munro.1991. Mathematical modeling of hot air drying of sweet potato slices. *International Journal of Food Science and Technology,* 26(1):99 - 109

Diamente, L. M. and P. A.Munro.1993. Mathematical modeling of the thin layer solar drying of sweet potato slices. *Solar Energy,* 51(4):271–276.

Diamante, L. M., R.Ihns, , G.P.Savage, ,andL.Vanhanen. 2010. A new mathematical model for thin layer drying of fruits. *International Journal of Food Science and Technology*,45(9):1956-1962.

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

Doymaz, I.2007a. The kinetics of forced convective air-drying of pumpkin slices. *Journal of Food Engineering,*79(1): 243-248.

Doymaz, I.2007b. Air-drying characteristics of tomatoes. *Journal of Food Engineering*, 78(4): 1291–1297.

Erenturk, S., M. S.Gulaboglu, and S.Gultekin.2004. The thin layer drying characteristics of rosehip. *Biosystems Engineering* 89(2): 159-166.

Evin, D.2011. Thin layer drying kinetics of gundeliatournefortii L. *Food. Bioproduction Process*.doi:10.1016/j.fbp.2011.07.002.

Falade, K. O. and E. S.Abbo.2007. Air-drying and rehydration characteristics of date palm (*Phoenix dactylifera L.*) fruits. *Journal of Food Engineering,* 79(2): 724-730.

Flores, M.J.P, V. G Febles, J.J.C Pérez, G Dominguez, J.V.M Mendez, E.P Gonzalez, and G.F.G Lopez. 2012. Mathematical modelling of castor oil seeds *(RicinusCommunis)* drying kinetics in fluidized bed at high temperatures. *Industrial Crop Production.* 38:64-71.

Goyal, R. K., A. R. P.Kingsley, , M. R.Manikantan, and S. M.Ilyas. 2006. Thin-layerdrying kinetics of raw mango slices. *Biosystems Engineering,* 95(1): 43–49.

Iguaz, A., M. B.San Martin, , J. I.Mate,, T.Fernandez, and P.Virseda. 2003. Modellingeffective moisture difusivity of rough rice (Lido cultivar) at low drying temperatures. *Journal of Food Engineering*, 59(2): 253-258.

Johnson, P. N. T., G.Brennan,and F. Y.Addo-Yobo.1998. Air-drying characteristics of plantain*(Muss* AAB). *Journal of Food Engineering*, 37(2): 233-242.

Kadam, D M, R A Wilson, and S Kaur(2010).Determination of biochemical properties of foam mat dried mango powder. *International Journal of Food Science and Technolology,* 45(8): 1626-1632.

Kaya, A., O.Aydin, , C.Demirtas, and M.Akgün. 2007. An experimental study on the drying kinetics of quince. *Biosystems Engineering*, 212(2): 328-343.

Maskan, M.2000. Microwave /air and microwave finish drying of banana. *Journal of Food Engineering*, 44(2): 71-78.

Maskan, A., S.Kaya, , and M.Maskan. 2002. Hot air and sun drying of grape leather (pestil). *Journal of Food Engineering*, 54(1): 81–88.

Meziane S. 2011. Drying kinetics of olive pomace in a fluidized bed dryer. *Industrial Crop Production.* 52(3):1644-1649.

Midilli, A., H.Kucuk, and Z.Yapar.2002. A New model for single-layer drying. *Drying Technology,* 20(7): 1503-1513.

Muthukumarappan, K. and S Gunasekaran.1994. Moisture diffusivity of adsorption Part:Germ. *Transaction of ASAE*, 37 (4): 1263-1268.

Nguyen, M.H. and W. E.Price.2007. Air-drying of banana: Influence of experimentalparameters, slab thickness, banana maturity and harvesting season. *Journal of Food Engineering,* 79(1): 200-207.

Prachayawarakorn, S., W.Tia, , N.Plyto, and S.Soponronnarit. 2008. Drying kinetics and quality attributes of low-fat banana slices dried at high temperature. *Journal of Food Engineering,* 85(4): 509-517

Radhika G.B, S.VSatyanarayana,andD.G Rao. 2011. Mathematical model on thin Layer drying of Finger Millet

(Eluesinecoracana). *Advance Journal Food Science Technology*. 3(2):127-131.

Ratti, C. and A.S.Mujumdar.1997. Solar drying of foods.Modeling and numerical simulation. *Solar Energy*, 60 (3-4): 151-157.

Rayaguru, K. and W.Routray.2012. Mathematical modeling of thin layer drying kinetics of stone

apple slices. *International Food Research Journal,* 19(4): 1503-1510

Rocha, T., A.Lebert, and C.Marty-Audouin.1993.Effect of pretreatments and drying conditions on drying rate and colour retention of basil (*Ocimumbasilicum*).*LebensmittelWissenschaft und Technologie*, 26: 456-463.

Sacilik, K., R.Keskin, and A. K. Elicin.2006. Mathematical modeling of solar tunnel drying of thin layer organic tomato. *Journal of Food Engineering*, 73(3): 231–238.

Saeed, I. E., K.Sopian, and Z.ZainolAbidin.2006. Drying kinetics of Roselle (Hibiscus sabdariffa L.): dried in constant temperature and humidity chamber. Proc. SPS 2006.Edited by Muchtar.29th-30th August. Permata, Bangi, S.D.E., Malaysia: 143-148.

Sarsavadia, P. N., R. L.Sawhney, , D. R.Pangavhane, and S. P.Singh. 1999. Drying behavior of

brined onion slices. *Journal of Food Engineering,* 40(3): 219-226.

Sereno, A.M. and G.L Medeiros.1990. A simplified model for the prediction of drying rates for foods. *Journal of Food Engineering*, 12(1): 1-11

Shen F, L Peng, Y Zhang,J Wu, X Zhang, G Yang, H Peng, HQi, and S Deng. 2011. Thin-layer drying kinetics and quality changes of sweet sorghum stalk for ethanol production as affected by drying temperature. *Industrial. Crop Production.*, 34(3):1588-1594.

Singh, G. D., R.Sharma, ,A. S.Bawa, and D. C.Saxena. 2008. Drying and rehydration characteristics of water chestnut (*Trapanatans*) as a function of drying air temperature. *Journal of Food Engineering,* 87(2): 213-221.

Sobukola, O. P., O. U Dairo, and V. O.Odunewu.2008. Convective hot air drying of blanched yam slices. *International Journal of Food Science and Technology*, 43(7): 1233-1238.

Sobukola, O. P. 2009. Effects of pre-treatment on the drying characteristics and kinetics ofokra. *International Journal Food Engineering*, 5(2): 6-19.

Toğrul, I. T. and D Pehlivan.2002. Mathematical modeling of solar drying of apricots in thin layers. *Journal of Food Engineering,* 55(3): 209-216.

Togrul, I. T. and D.Pehlivan.2003. Modeling of drying kinetics of single apricot. *Journal ofFood Engineering,*58(1): 23-32.

Tunde-Akintunde T. Y. and A. A.Afon.2009. "Modelling of hot-air drying of pretreated cassava chips". *Agricultural Engineering International: the CIGR Ejournal,* 12(2): 34 - 41

Velić, D., M.Planinić, , S.Thomas, and M.Bilić.2004. Influence of airflow velocity on kinetics of convection apple drying. *Journal of Food Engineering,* 64(2): 97-102.

Verma L. R, R. A Bucklin, , J. B Endan, and F. T.Wratten. 1985. Effects of drying air parameters on rice drying models. *Transaction of. ASAE,* 28(1): 296-301.