DRYING KINETICS OF PLANTAIN SLICES USING A MIXED SOLAR DRYER

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ABSTRACT

The drying kinetics of plantain slices was studied using the thin layer drying characteristics of plantain slices in a mixed mode convectional solar dryer. The diffusivity and drying models were obtained to describe the drying curve. The dryer used for the experiment had an average drying chamber temperature ranging from 34 - 50°C, while eight commonly used thinlayer drying models were used for drying curve modeling. The models performance was evaluated by comparing the coefficient of determination (R^2) and Root Mean Square Error (RMSE). The drying curve showed a reduction of moisture content with increased drying time of plantain slices in the solar dryer. It was observed that the drying rate curve followed slightly the average daily temperature variation in the study. The variation of moisture ratio (MR) was found to exponentially decrease with increased drying time. The Midilli model showed the best fit to the experimental drying data as compared to other models tested in the R^2 and RMSE values obtained. Midilli model had the lowest values of R^2 and RMSE. The diffusion mechanism could be used to describe the drying of plantain slices which was found to be in the falling rate period. The diffusion coefficient (D_{eff}) obtained for plantain slices was 1.46x 10^{-9} m^2s^{-1} was within the established standard for food products.

Keyword: Plantain, Drying Kinetics, Diffusion coefficient, Solar drier, Thinlayer Drying (TLD)

INTRODUCTION

Plantain (*Musa spp.*) is a major source of carbohydrate for millions of people in West Africa. In Nigeria, plantain is being used as an ingredient in many traditional recipes. A popular method of preparing the unripe plantain is cutting them into slices and drying. The dried slices are then ground into flour. The flour is prepared into an elastic pastry which is eaten with vegetable soup. Also flour made from freshly ripe plantain has been used in making bread, biscuits and instant flour (Folayan and Bifarin, 2011).

In the rural areas where these plantains are produced open sun drying is employed in the drying of plantain slices. The disadvantages of this method include risk of spoilage due to adverse climatic conditions like rain, wind and dust, contamination by insect pest and undesirable colour changes. Therefore, the use of solar and hot air dryers which are far more rapid and which provide uniformity and hygienic drying for industrial food drying processes have become inevitable (Karathanos and Bellesiotis, 2002). However, increased cost of fossil fuel and lack of electricity in these rural areas has led to a search for alternative energy sources such as solar energy for agricultural products. According to Sacilik *et.al* (2006) open sun drying is a well-known and established preservation method that reduces moisture in agricultural produce and also prevents deterioration within a time regarded as the safe storage period. Despite its many disadvantages, in rural areas of Nigeria where majority of this crop is produced, drying of plantain is mostly achieved by open sun drying. Open sun drying usually exposes the product to contamination by insect pests, dust and damage by unfavourable weather conditions. Simple solar dryers in which heated air rises by natural convection through the product has been proposed for rural areas (Basunia and Abe, 2001). Low cost locally available material are usually used in the construction of these dryers, consequently eliminating dependence on electricity and fossil fuels which are scarce commodities in these rural areas. The solar dryer also reduces contamination of the product and encourages the use of renewable energy in our rural areas. Cost effectiveness and hygienic ways of preserving foods are of great importance given the prevailing insecurity in food supplies throughout the world (Sobukola *et al.,* 2007).

Vizcarra-Mendoza *et al.* (2003) reported that an important factor in drying agricultural produce is the quick removal of moisture at a temperature that does not seriously affect the flavour, texture and colour of the product. A low temperature in the beginning of drying may encourage microorganisms' growth before the grain is adequately dried. Drying characteristics of agricultural products and materials are usually studied using drying kinetics of such. Knowledge of the drying properties would assist in modeling the drying kinetics of such material.

Modeling of drying kinetics fall into three categories, namely; theoretical, semi- theoretical and empirical (Midilli *et al*., 2002; Ojediran and Raji, 2010; Sobukola and Dairo, 2007). The theoretical approaches account for only the internal resistance to moisture transfer while the semi-theoretical and empirical approaches consider only the external resistance to moisture transfer between the product and air (Lahsasni *et al*., 2004).

The equation for thin layer drying of grains in terms of moisture or mass transfer is generally given by Equation (1) as given by Brooker *et al. (*1992), where Equation (2) is obtained by integration of Equation 1.

$$\frac{\partial M}{\partial t} = k(M - M_e) \qquad 1$$

$$\frac{M - M_e}{M_o - M_e} = e^{-kt} \qquad 2$$

Where M represents the moisture content (% d.b) at drying time t (h), M_e is the equilibrium moisture content (% d.b), k represents the drying rate constant (h^{-1}) and M_o is the initial moisture content, (% d.b) at t = 0.

A dimensionless ratio given by the LHS of Equation (2) is usually referred to as Moisture Ratio (MR), however, according to several researchers on solar drying (Tunde-Akintude and Afon, 2010; Sobukola and Dairo, 2007) the relative humidity of the drying air varies continuously during solar drying and the values of M_e are relatively small compared to M and M_o, hence thin layer drying equation is usually represented by Equation (3).

$$MR = \frac{M}{M_o} = e^{-kt} \qquad 3$$

Diffusivity is a very important parameter used to indicate the flow of moisture out of the material being dried(Vizcarra-Mendoza *et al*., 2003) usually considered during drying. Moisture diffusivity is influenced mainly by moisture content and temperature of the material. Drying process in the falling rate period is limited by the diffusion of moisture from the inside to the surface layer, represented by Fick's law of diffusion (Crank, 1975) as given by equation 4. The analytical solution of Equation (4) for infinite slab is given by Equation (5) on assumption of uniform initial moisture distribution, negligible external resistance, constant diffusivity and negligible shrinkage according to Crank (1975).

$$\frac{\partial M}{\partial t} = D_{eff}\nabla^2 M \qquad 4$$

$$MR = \frac{8}{\pi^2}\left[\exp\left(\frac{-\pi^2 D_{eff}\, t}{4L^2}\right) + \frac{1}{9}exp\left(-9\frac{\pi^2 D_{eff}\, t}{4L^2}\right) + \frac{1}{25}exp\left(-25\frac{\pi^2 D_{eff}\, t}{4L^2}\right) + ..\right] \qquad 5$$

For long drying times the analytical solution is usually represented with Equation (6) by taking the first term of series solution expressed in a logarithmic form as used by several researchers including Doymaz (2012). The effective moisture diffusivity is then obtained from the slope of a straight line plot of *Ln*(*MR*) versus drying time given by Equation (6) and evaluated from Equation (7) where *k* is the slope of Equation (6).

$$\text{Ln}(MR) = \ln\frac{8}{\pi^2} - \left(\frac{\pi^2 D_{eff}}{4L^2}\right)t \qquad 6$$

$$K = \frac{\pi^2 D_{eff}}{4L^2} \qquad 7$$

where, D_{eff} is the effective moisture diffusivity in $m^2.s^{-1}$, t is the time (*s*), *n* is a positive integer, *L* is the half-thickness of samples (m).

There have been many researches on experimental studies and mathematical modeling of thin layer characteristics using conventional, open sun drying and solar for different agricultural products such as leafy vegetables (Tunde-Akintunde *et al.,* 2005, Sobukola and Dairo, 2007, Sobukola *et. al,* 2007); Millet (Ojediran and Raji, 2010); apple slices (Meisami-asl *et al.,* 2010); sultana grapes (Yaldiz *et al.,* 2001); strawberry (Akpinar and Biser, 2006) and sesame seed (Dairo and Olayanju, 2012). This study investigated the drying kinetics of plantain slices in a solar dryer under natural air convection using the thinlayer properties.

MATERIALS AND METHOD

Solar dryer

A mixed mode type natural convection solar dryer developed at the Department of Agricultural Engineering, Federal University of Agriculture, Abeokuta was used for the study. The dryer consisted of a solar collector, a drying chamber and a transparent roof to allow direct solar radiation into the drying chamber (Fig.1). The solar collector of dimensions 45 x 53 x 20 cm was covered with a 2.5 mm thick glass with the drying chamber (50 x 45 x 45 cm) consisting of three layers of tray. The air vent was covered with a perforated netting to prevent insects from entering and infesting the samples in the dryer. The solar collector and transparent roof were both inclined at 17^o using latitude of location according to Alamu *et.al* (2010).

Materials

Freshly harvested plantain were procured at a popular market in Abeokuta, Ogun State. They were washed, hand peeled and sliced to 3 mm thickness using a mechanical slicer. The initial moisture contents of the slices were determined by oven drying at 102^{o}C for 6 hour according to ASAE standards (ASAE, 1998).

Experimental procedure

The solar drier was positioned in the open with the collector facing the direction of the sun and a no-load test was carried out by taking the temperature inside the collector, the drying chamber and the ambient air using a digital infrared thermometer at 1h-interval for 9h a day starting from 08:00 to 18:00 hr, for three days.

Single layer of 3 mm slices of plantain slices of known initial mass were spread on the drying trays in the drying chamber of the solar dryer to determine the thinlayer drying characteristics. The losses in weight of the slices were monitored at a 1hour-interval by using an electronic weighing balance (Mettler, model AE 240) with an accuracy of ±0.01 g. All measurements were repeated three times to obtain an average value which was used in the analysis. The moisture content at hourly basis was calculated from the initial moisture content and weight loss using Equation (8) (Ojediran and Raji 2010)

$$M_t = \frac{M_{imi-w_i}}{m_i - w_i} \quad 8$$

Where M_t = moisture content at any time t (% w.b.)

M_i = initial moisture content (% w.b.)

m_i = initial mass of sample (g)

w_i = weight loss at time t (g)

Thinlayer drying models

The experimental data were fitted to ten commonly used thinlayer drying models presented in Table 1 to determine their suitability in describing the thinlayer behavior of plantain slices using Datafit version 9.0.59 (Oakdale, 2008). The coefficient of Determination (R^2) and Root Mean Square Error (RMSE) were used as criteria for adequacy and goodness of fit for the models. The best model for describing the thin layer characteristics of solar drying of plantain slices was selected as the one with highest R^2 and the least RMSE (Ertekin and Yaldiz, 2004; Dairo and Olayanju, 2012).

RESULTS AND DISCUSSION

The initial moisture content for the plantain slices was found to be 60.9 ± 0.9 % (w.b). The temperature distribution on a typical day during the no-load test is as shown in Fig. 2. The temperature of the ambient air ranged from 31 to 36 °C while that of the collector varied from 35 to 61°C and the drying chamber temperature from 34 to 50 °C. The maximum temperature was reached at 13h for ambient while it was between 13 and 15hr for the collector and drying chamber. The temperature in the drying chamber was always higher than the ambient air temperature throughout the duration of the experiment thus confirming that the dual mode solar dryer could raise the temperature of the drying chamber for effective drying.

The drying curve shown in Fig 3a depicts the reduction of moisture content with increased drying time in the solar dryer. The moisture content reduced with increased drying time as expected and observed by several other researchers. The rate of water removal was highest in the first 2 hours of drying as shown in the drying rate curve (Fig 3b) after which removal rate began to reduce until it appeared constant between 13:00 and 16:00 h. After 16:00 h there was a decreased drying rate. It could be observed that the drying rate curve slightly followed the average daily temperature variation observed in the study. The thinlayer drying could be described as a falling rate drying as shown in Fig3a, where diffusion has been described by several researchers as the most likely mechanism, where moisture movement is from the interior to the surface of the product (Sobukola et al., 2007).

A plot of the observed dimensionless ratio (MR) against drying time is shown in Fig 4. The variation of moisture ratio was observed to exponentially decreased with increased drying time of cassava slices under natural convective solar drying similar to observation made by other researcher(Ojediran and Raji, 2010; Ajibola 1989).

Model evaluation

The values for the coefficient of Determination (R^2) and RMSE for the evaluated models are presented in Table 2. The coefficient of Determination (R^2) ranged from 0.967 to 0.979 while the RMSE values obtained ranged from 0.0054 to 0.0198.

A t-test for the identified models revealed significant differences ($p < 0.05$) between the models tested; consequently the Midilli model was selected based on the significant test as the best fits for solar drying of cassava slices under natural convection. A plot of Moisture Ratio (MR) against time using Midilli model is shown in Fig 4.

Effective diffusivity

The diffusivity was obtained by evaluating Equation (7) with the slope of Equation(6) obtained by plotting experimental data in terms of natural logarithm of moisture ratio against drying time as shown in Fig 5. The effective diffusivity (D_{eff}) was obtained as 1.46×10^{-9} m^2s^{-1} which was within the range of 10^{-12} and 10^{-8} reported for food materials by Madamba *et. al.(*1996).

CONCLUSION

The drying kinetics of plantain slices in a mixed solar drying system was investigated by determining the thinlayer drying constant for the Midilli model that best describes the solar drying in a mixed solar dryer. The solar dryer used for the experiment with average drying chamber had temperature ranging between 34 and 50°C. The drying curve showed a reduction of moisture content with increased drying time of plantain slices in the solar dryer. The variation of moisture ratio an indicator of drying rate was observed to exponentially decrease with increased drying time. The experimental data was fitted to different drying models using the coefficient of Determination (R^2) and RMSE as fitness criteria. The Midilli model showed best fit to the experimental drying data as compared to other models tested. The Midilli model was significantly different from other models considering the R^2 value and RMSE. The diffusion mechanism could be used to describe the drying of plantain slices which was found to be in the falling rate. The obtained effective diffusion coefficient (D_{eff}) of 1.46 x 10^{-9} m^2s^{-1} was within the established standard for food products. The drying kinetic parameters obtained could be used in the improvement of local equipment, processes and research study involving plantain slices under natural convection.

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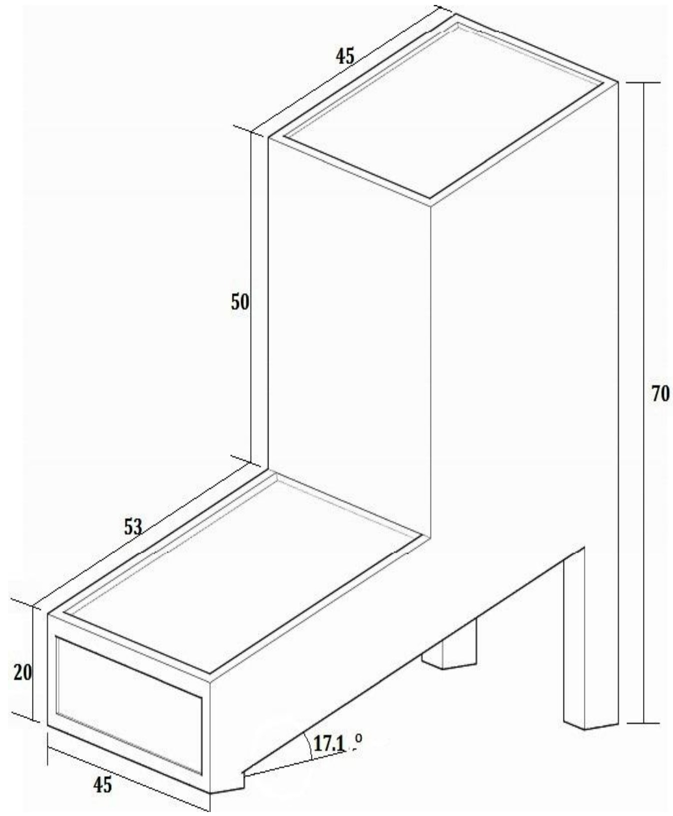

Fig 1. Isometric drawing of the solar dryer

Table 1. Mathematical models applied to the Solar drying of Plantain Slices

No	Model name	Equation
1.	Midilli	$MR = a * Exp(-kt^n) + bt$
2.	Logarithm	$MR = a * Exp(-kt) + c$
3.	Modified Page	$MR = a * Exp(-kt^n)$
4.	Page	$MR = Exp(-kt^n)$
5.	Weibull	$MR = Exp\left(-\left(\frac{t}{a}\right)^n\right)$
6.	Wang &Singh	$MR = 1 + at + bt^2$
7.	Henderson & Pabis	$MR = a * Exp(-kt)$
8	Logit	$MR = \frac{a}{(1 + a * Exp(kt))}$

Source: Meisami-asl *et al.*(2010); Ojediran and Raji (2010)

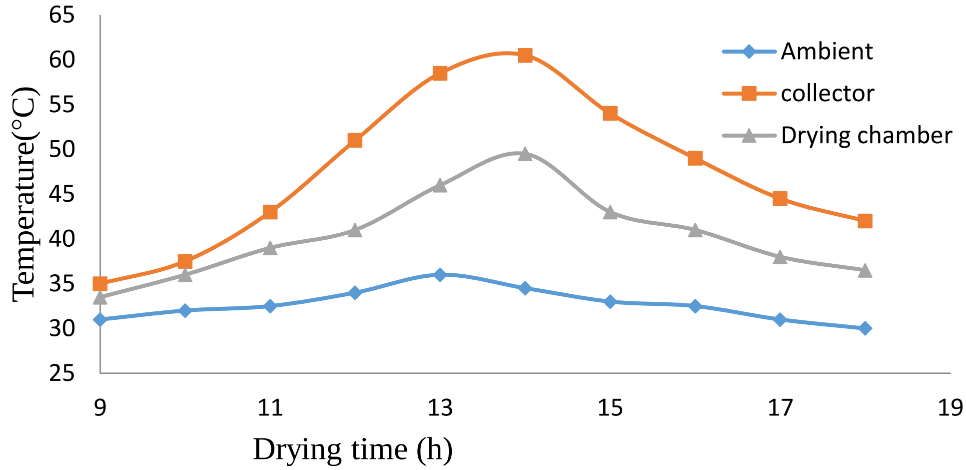

Fig 2 . Hourly temperature variation in the ambient air, solar collector and drying chamber on a typical day during the drying experiment

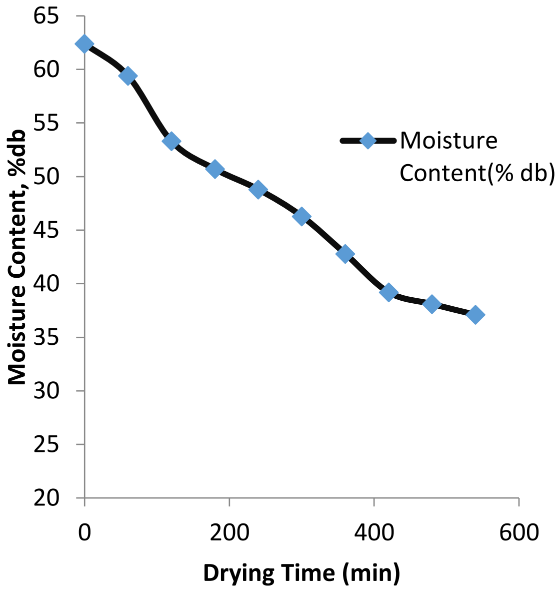

Fig 3a. Drying curve of plantain slices in solar drying

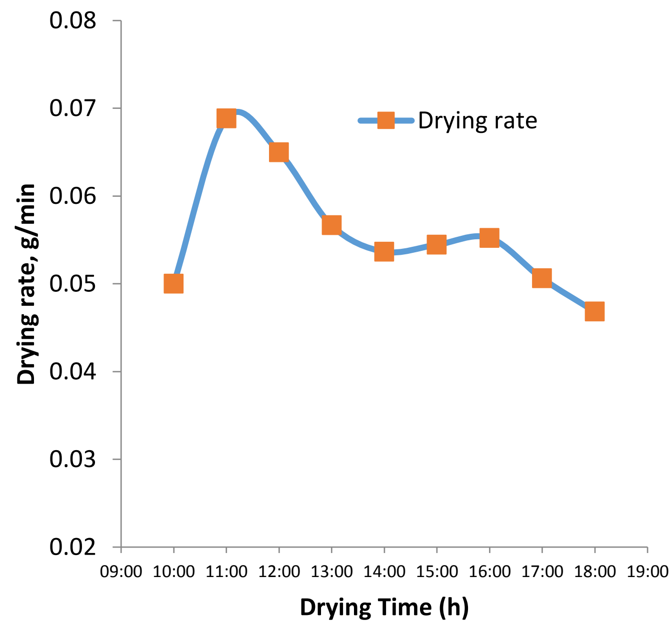

Fig 3b. Drying curve of plantain slices in solar drying

Table 2. TLD models, model constants with the Coefficient of Determination (R^2) and Standard Error of Estimates for plantain slices using solar dryer

	Model Parameters						
MODEL	a	b	c	k	n	**R^2**	RMSE
Midilli	**1.045**	-0.043		-0.041	1.542	0.979	0.0054
Logarithm	0.789		0.302	0.145		0.960	0.0141
Modified Page	1.048			0.075	0.896	0.970	0.0161
Page				0.087	0.910	0.967	0.0184
Weibull	15.214	0.861				0.957	0.0194
Wang &Singh	-0.047	0.015				0.956	0.0198
Henderson & Pabis	0.987			0.157		0.944	0.0181
Logit	150.58			0.057		0.954	0.0191

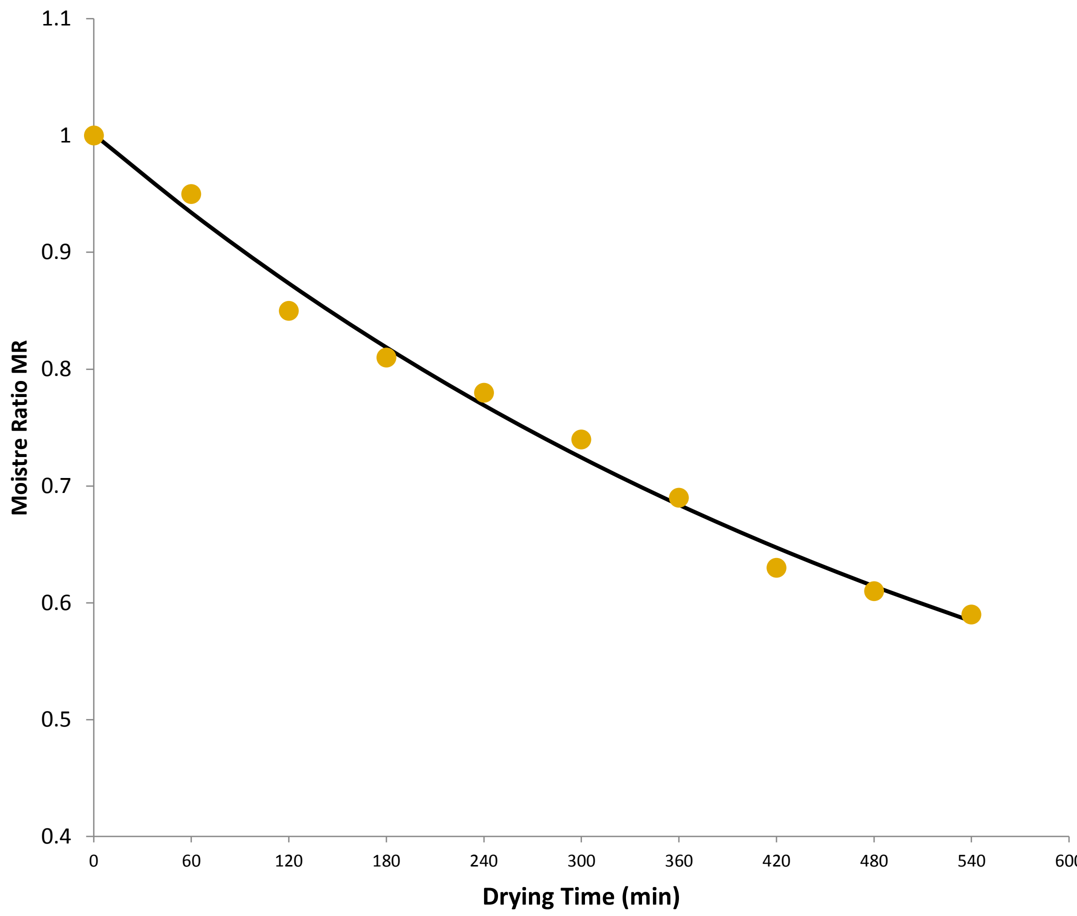

Fig 4. Plot of observed and predicted Moisture Ratio(MR) against drying time of platain slices using Midilli model .

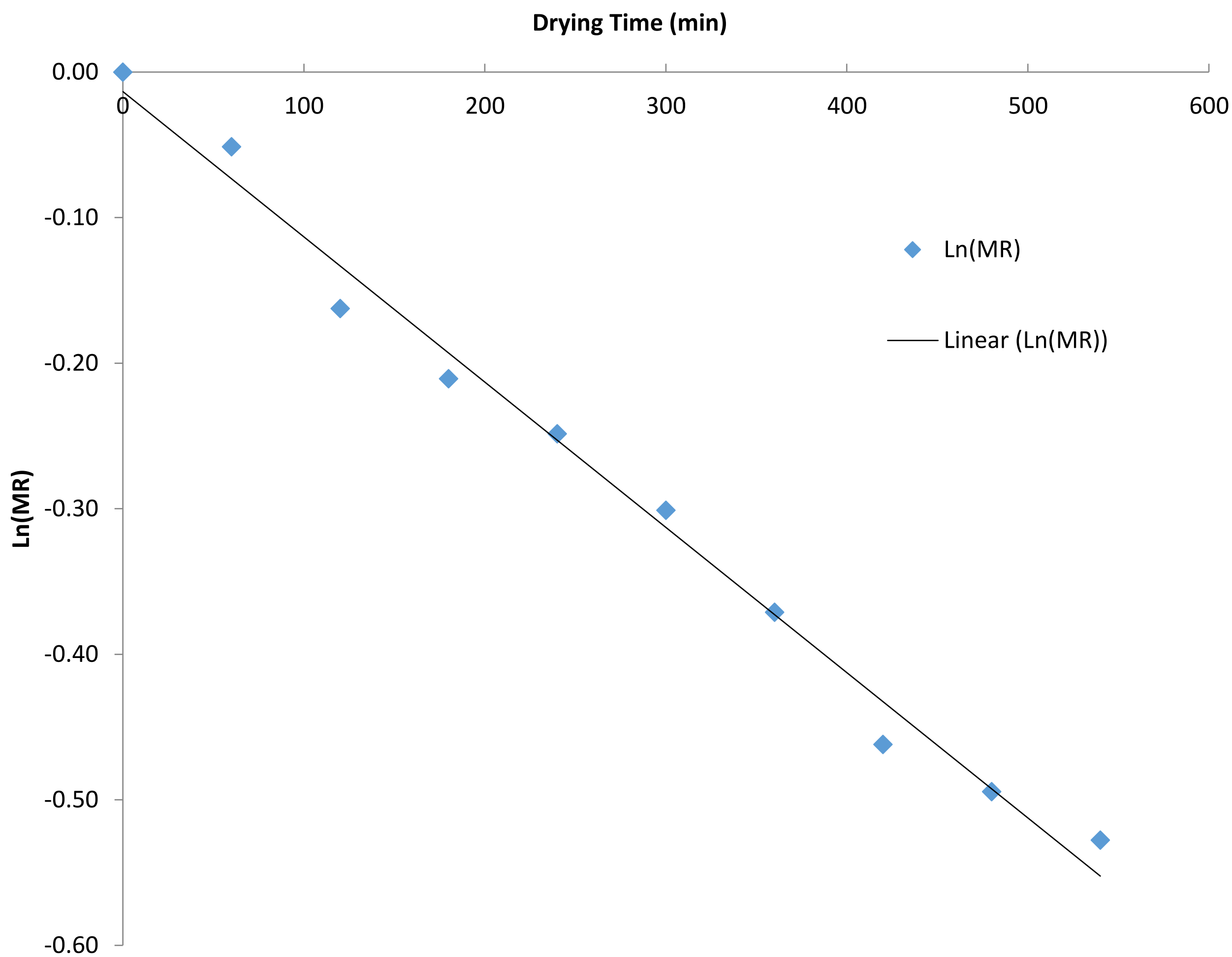

Fig. 5 Plot of Ln(MR) against drying time for plantain slices