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Thin Layer Drying Kinetics and Modelling of Okra (Abelmoschus Esculentus (L.) Moench) Slices under Natural and Forced Convective Air Drying

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ABSTRACT
The effect of sample thickness (10 and 20 mm), method of drying (open sun, solar and hot air drying) and drying air temperature (50, 60 and 70 °C) on the drying characteristics and kinetics of okra slices were investigated. The results showed that sample thickness, method of drying and drying air temperature significantly (P = 0.05) affected the drying rate and thus the drying time. It was observed that okra slices would dry perfectly within 216 – 240 h, 192 -216 h, and 12 – 19 h under open sun, solar and hot air drying, respectively. Irrespective of the drying method, all the samples dried in the falling rate period with no constant rate period. Four thin-layer semi-empirical mathematical drying models (Newton, Page, Henderson and Pabis, and Logarithmic models) were fitted to the experimental drying curves. The models were compared using the coefficient of determination (R^2) and the root mean square error (RMSE). The logarithmic model has shown a better fit to the experimental data obtained from the open sun, solar and hot air drying respectively as relatively compared to other tested models. Correlation between the model parameters and the drying air temperature (under hot air drying) to calculate moisture ratio in relation to the drying time were also determined. The transport of water during drying was described by application of Fick's diffusion model and the effective moisture diffusivity was estimated. The value ranges from 0.253 to 0.901 × 10^{-10} m^2/s for open sun, 0.31 to 1.01 × 10^{-10} m^2/s for solar drying and 3.29 to 14.7 × 10^{-10} m^2/s for hot air drying, respectively. The Arrhenius-type relationship describes the temperature dependence of effective moisture diffusivity and was determined to be 16.74 kJ/mol and 10.39 kJ/mol for 10 and 20 mm sample sizes, respectively.
Keywords: Okra; Open sun drying; Solar drying; Hot air drying; Mathematical modelling; Effective moisture diffusivity.

1.0 INTRODUCTION
In most part of the world, okra (Hibiscus/ Abelmoschus esculentus) also called 'lady finger' is considered as an important vegetable crop, for its economical and nutritive values. It is one of the main vegetable crops cultivated in tropical countries and warmer parts of temperate countries. The largest ten producers are India, Nigeria, Iraq, Côte d'Ivoire, Pakistan, Egypt, Benin, Cameroon, Ghana and Saudi Arabia. World okra production was 6,876,584 MT, while Nigeria okra production in 2012 was 1100000 MT (FAOSTAT, 2012). Okra is grown for its fibrous pods containing seeds (Kumar et al., 2011). It is a source of protein, vitamins C and A, iron, calcium, dietary fiber and low saturated fat (Doymaz, 2005). Freshly harvested okra has very high moisture content (88-90% wet basis) with safe moisture content for storage (10% wet basis) (Shivhare et al., 2000). Due to its high moisture content, its shelf life does not increase (Kumar and Prasad, 2010), because it is subjected to rapid deterioration, resulting in chemical, physical and biological changes. Because of its sensitivity to storage, most fresh okras are preserved in some form. One of the most widely used methods of food preservation is drying which also extends the shelf-life of food. Drying processes has been one of the oldest technologies among the industrialized processes in the preservation of agricultural food materials or products. This is gaining forces as one of the promising techniques and thus become an object for research studies. It is defined as a process of moisture removal due to simultaneous heat and mass transfer (Ertekin and Yaldiz, 2004; Waewsak et al., 2006).

The traditional way of drying food materials has been by open sun drying, however, this is not always suited to large-scale production due to lack of ability to control the drying conditions, the uncertainties of ambient conditions, large area requirements, contamination of dust and insect and rodent infestation (Ertekin and Yaldiz, 2004; Togrul and Pehlivan, 2004). To avoid these problems drying equipments were designed and produced on the basis of drying test. The studies based on simulation models are needed for design and operation of dryers as well as useful in improving the existing drying system. Thus, several researchers in recent times have investigated the drying characteristics or behavior of different food materials including fruit and vegetables, sea food products using different drying methods such as open sun drying for grapes ((Togrul and Pehlivan, 2004), fish (Jain and Pathare, 2007), and onion slices (Arslan and Ozcan, 2010); solar drying for green pepper (Akpinar and Bicer, 2008), strawberry (Beltagy et al., 2007), Brook mangoes (Dissa et al., 2011), and okra (Doymaz, 2011; Ismail and Ibn Idriss, 2013)); and hot air drying for red pepper (Simal et al., 2005), okra (Doymaz, 2005), tomato (Doymaz, 2007), and carrot (Zielinska and Markowski, 2010), respectively.

The drying characteristic curves of most of these food materials were modeled using different drying models such as the Newton model (O'Callaghan et al., 1971), Page model (Akpinar et al., 2003), Henderson and Pabis model (Karathanos and Belessiotis, 1999), logarithmic model (Yaldiz et al., 2001), two term exponential model (Akpinar et al., 2003). For example, the page model was found to best describe the drying behavior of potato, red pepper and tomato under hot air drying (Akpinar et al., 2003; Simal et al., 2005; Doymaz, 2007) while exponential model for mulberry under open sun (Doymaz, 2004) and Newton model for strawberry under solar drying (Beltagy et al., 2007) were found to best describe their drying behavior, respectively. Okras being one of the world traded vegetable in both fresh and processed form, few researchers have studied the drying of this vegetable either as untreated or pretreated form using hot air drying (Doymaz, 2005; Sobukola, 2009; Doymaz, 2011; Ismail and Ibn Idriss, 2013; Honore et al., 2014). However, information on the drying of okra using natural convection is seldom scarce.

The objective of this study is to investigate the drying characteristics and kinetics of okra of different thickness under open sun and solar (natural convection) drying as well as with different sample size and drying air temperature under hot air drying (forced air convection); and to model the drying characteristics and kinetics by application of known semi-empirical mathematical drying models in the literature.

2.0 MATERIALS AND METHODS

2.1 Raw material

Fresh okras (Abelmoschus esculentus (L.) Moench) were purchased from the local market of Ogbomoso, Nigeria. The okras were washed with tap water and then cut into rectangular pieces of thickness 10 and 20 mm, respectively. The okra slices were then subjected to open sun, solar and hot air drying respectively.

2.2 Drying equipment

The drying experiments were conducted in a metal tray placed in the open sun and solar dryer respectively. The solar dryer used was fabricated and consists essentially of a solar collector and drying chamber constructed with wooden planks with cross-sectional areas of $1.0m^2$ x $1.5m^2$, respectively. Transparent polythene framed in wood served as the top cover for the collector and the drying chamber.

2.3 Open sun air drying

Approximately 100 g each of sliced okra samples of thickness 10 and 20 mm were spread in different metal tray respectively and then placed in the open sun from 10.00 a.m to 4.00 p.m daily. The dry bulb temperature and relative humidity of the surrounding environment was taken four times between 12 noon and 4.00 p.m daily. At the end of drying period each day, samples were weighed and recorded. This was done until approximately 100% (dry weight basis (d.b)) moisture content was obtained for the dried sample.

2.4 Solar air drying

Approximately 100 g each of sliced okra sample of 10 and 20 mm thickness were spread on a different metal tray respectively and then placed in a solar dehydrator. The solar dehydrator was left in the open sun environment. The dry bulb temperature and relative humidity within the drying chamber was taken four times between 12 noon and 4.00 p.m daily. At the end of drying period each day, the samples were weighed and recorded. This was done until an approximately 100% d.b moisture content was obtained for the dried sample.

2.5 Hot air drying

Approximately 100 g of sliced okra sample with thickness of 10 and 20 mm respectively, were spread in metal trays and each placed in an oven dryer (Uniscope SM 9053 A Laboratory oven, Surgifriend Medicals, England). Drying was carried out at combinations of three dry bulb temperatures (50, 60 and 70 ^oC) and two sample thickness (or size diameter) (10 and 20 mm). At one hour interval, samples were withdrawn from the dryer and weighed until approximately 100% (dry weight basis (d.b)) final moisture content was obtained. The moisture content of both the fresh and dried samples was determined according to AOAC (1995). The drying rate of the samples was calculated based on weight of water removed per unit time and per kilogram of dry matter (solid) and expressed in units of $kgkg^{-1}$ h^{-1}(Dandamrongrak et al., 2003; Agarry et al., 2005, Agarry et al., 2006).

2.6 Mathematical modelling

Thin-layer mathematical drying models describe the drying phenomenon in a unified way regardless of the controlling mechanisms (Kingsly et al., 2007). In thin layer drying, the moisture ratio during drying is calculated according to Eq. (1):

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

Where MR is the dimensionless moisture ratio, M, the average moisture content at time t, M_o, the initial moisture content, and M_e, the equilibrium moisture content respectively, on dry weight basis.

During thin layer drying of okra in open sun and solar dryer, the samples were not exposed to uniform relative humidity and temperature continuously. As a result of this, the equilibrium moisture content could not be determined and since this is usually not high for food materials (Togrul and Pehlivan, 2004; Waewsak et al., 2006), the equilibrium moisture content was assumed to be zero. Thus, the moisture ratio (Eq. 1) was simplified according to Pala et al. (1996) and Kingsly et al. (2007) to:

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

The recorded moisture contents for each sample were then used to plot the drying curves. Four known semi-empirical mathematical drying models that expresses relationship between MR and the drying time, t as presented in Table 1 were applied to the drying curves obtained for each sample at each process variables using the non-linear regression analysis as to select the best model (based on the quality of fit) that describes the drying characteristics or behavior. Some of these models are recently used for determination of moisture ratio with drying time by Hii et al. (2009), Ismail and Ibn Idriss (2013) and Khawas et al. (2014).

The regression analysis was performed using MATLAB computer software package (version 6.5). The correlation coefficient (R^2) and root mean square error (RMSE) were major criteria for selection of the best model equation to describe the drying curve. For quality fit, R^2 value should be high and RMSE should be low (Demir et al., 2004; Erenturk et al., 2004). In order to evaluate the goodness of fit of the simulation provided by the proposed (best selected) model, different statistical parameters are usually used. In this study, the mean relative error (Eq. 3) and root mean square error (Eq. 4)(Nguyen et al., 2004; Simal et al., 2005) were calculated.

$$\%\text{E} = \frac{100}{N} \sum_{i=1}^{N} \left[MR_{\exp i} - MR_{prei} \middle/ MR_{\exp i} \right] \quad (3)$$

$$RMSE = \left[\frac{1}{N} \sum_{i=1}^{N} (MR_{\exp_i} - MR_{pre_i})^2 \right]^{\frac{1}{2}} \quad (4)$$

Where N, total number of observations, $MR_{\exp i}$, experimental moisture ratio values and MR_{prei}, predicted moisture ratio values. These modules have been used in the literature to evaluate the goodness of fit of different mathematical models. It is generally considered that %E values below or equal to 10% give a good fit (Park et al., 2002; Simal et al., 2005).

Table1 Mathematical model of drying curves

No	Model Names	Model Equation
1	Newton	MR = exp(-kt)
2	Page	MR = exp(-kt^n)
3	Henderson and Pabis	MR = a exp(-kt)
4	Logarithmic	MR = a exp(-kt) + c

a,c,n, empirical constants; k, drying constant; t, drying time; MR, moisture ratio.

2.7 Effective moisture diffusivity

For the determination of the effective moisture diffusivity (D_{eff}), a mathematical model was used based on Fick's second law of diffusion which expresses a relationship between the moisture ratio and the effective moisture diffusivity. The okra slices are assumed in the form of spherical and the Fick's second law of diffusion for spherical object is defined as follow:

$$\frac{\partial m}{\partial t} = D_{eff}\left[\frac{\partial^2 m}{\partial r^2} + \frac{2}{r}\frac{\partial m}{\partial r}\right] \qquad (5)$$

where m can be defined as the moisture content (dry or wet basis), moisture ratio, weight ratio and density. By using appropriate initial and boundary conditions and the assumptions of independence of diffusivities and temperature from interior moisture content, negligible volume shrinkage, and discounting the resistance of external convective mass transfer, Crank (1975) gave the analytical solution to Eq. (5) for object with spherical geometry as (Ochoa-Martinez and Ayala-Aponte, 2009):

$$\text{MR} = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left(\frac{-n^2\pi^2 D_{eff}\,t}{r^2}\right) \qquad (6)$$

Where D_{eff} is effective moisture diffusivity (m^2/s), t, drying time and r, radius of the spherical object (m). To be able to determine the effective moisture diffusivity, Eq. (6) may be simplified to a linear logarithmic form (Eq. 7) (Feng, 2000):

$$\ln MR = \ln\left(\frac{6}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff}\,t}{r^2}\right) \qquad (7)$$

The relationship between the effective diffusivities and temperature is assumed in the Arrhenius form of the type:

$$D_{eff} = D_o \exp\left[\frac{-E_a}{RT_{abs}}\right] \qquad (8)$$

where D_o is the pre-exponential factor of the Arrhenius equation (m^2/s), E_a is the activation energy (kJ/mol), R is the universal gas constant (kJ/mol K), and T_{abs} is the absolute temperature (K). By taking the natural logarithm of both sides, the above exponential form of Arrhenius can be transformed into a linear logarithmic form, Eq. (9):

$$\ln D_{eff} = \ln D_o - \left(\frac{E_a}{R}\right).\frac{1}{T_{abs}} \qquad (9)$$

Consequently, E_a can be obtained from the linear plot of $\ln D_{eff}$ against $1/T_{abs}$.

3.0 RESULTS AND DISCUSSION

The drying kinetics of okra were determined at different sample thickness of 10 and 20 mm under open sun , solar and hot air drying for average moisture contents from 809% d.b to 100% d.b(kg water/kg dry matter). Fig. 1(a – b) and Fig. 2 (a – c) shows the drying curves for the okra slices dried under open sun, solar and hot air drying respectively. According to Fig.1 (a) and Fig. 1(b) for open sun and solar drying respectively, it was observed that the drying of okra slices with different thickness has the falling rate period only. While, for hot air drying (Fig. 2) the drying of okra slices (irrespective of the sample thickness and drying temperature) is also in the falling rate period. This indicates that diffusion is most likely the dominant physical mechanism governing moisture movement within the okra pods. Similar observations have been reported by Akpinar and Bicer (2008) for long green pepper, Doymaz (2005), Sobukola (2009) and Ismail and Ibn Idriss (2013) for okra, Doymaz (2007) for tomatoes, Tunde-Akintunde and Afon (2010) for cassava, and Agarry and Owabor (2012) for banana.

Irrespective of the drying methods, initial drying rates were generally faster. This observation may be due to the higher initial moisture content of the okra. For the open sun, solar and hot air drying, the maximum drying rate decreased with higher sample thickness (Fig. 1 and Fig. 2). Fig. 3(a) (open sun), Fig. 3(b) (solar drying), and Fig. 4(a – c) (hot air drying) shows the dependence of moisture ratio on drying time. As expected for drying, moisture content dropped dramatically in the early drying stage, encompassing about one fourth of the overall time, and eventually changed little when close to a MR equivalent to moisture content of about 100% d.b. Initially, the abundance of free water on the product surface contributed to effortless moisture liberation. However, it might become much more difficult to expel water afterwards, when the product surface becomes harder due to shrinkage. Also, it could be observed that drying time increased at a higher sample thickness due to decreased drying rate. A similar observation has been reported (Maskan et al., 2002; Agarry and Owabor, 2012). Also, it is observed from Fig. 4(a – c) (hot air drying) that drying time decreased with increase in drying temperature due to higher moisture reduction at a higher temperature. The drying time ranges between 120 – 192 h for open sun drying, 72 – 168 h for solar drying and 10 -13 h for hot air drying respectively.

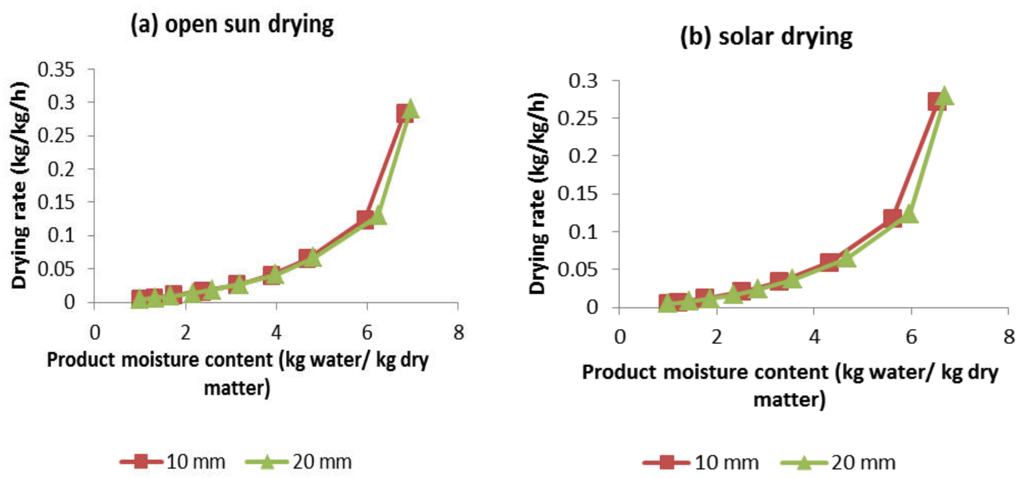

Figure 1: Drying rate curve for (a) the open sun drying of okra with thickness 10 mm and 20 mm and, (b) solar drying of okra with thickness 10 mm and 20 mm

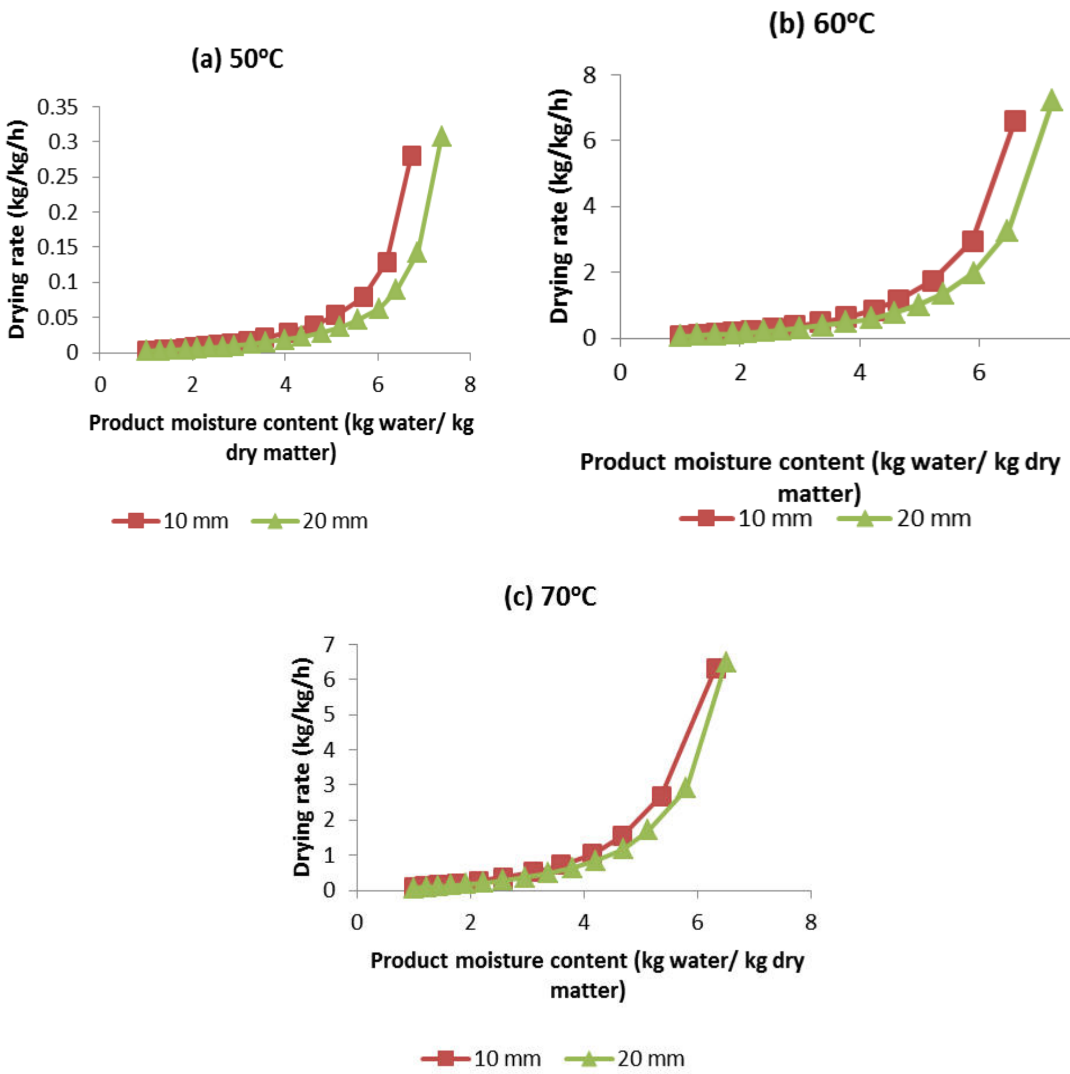

Figure 2: Drying rate curve for the hot air drying of okra with thickness 10 mm and 20 mm at (a) 50 °C, (b) 60 °C and (c) 70 °C

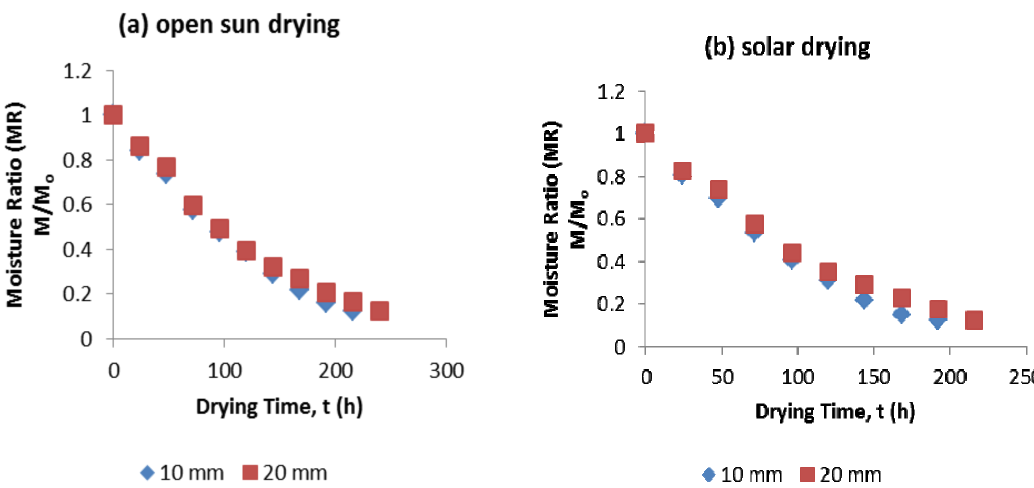

Figure 3: Moisture ratio variation with drying time for (a) open sun drying of okra, and (b) solar drying of okra slices of 10 and 20 mm thickness

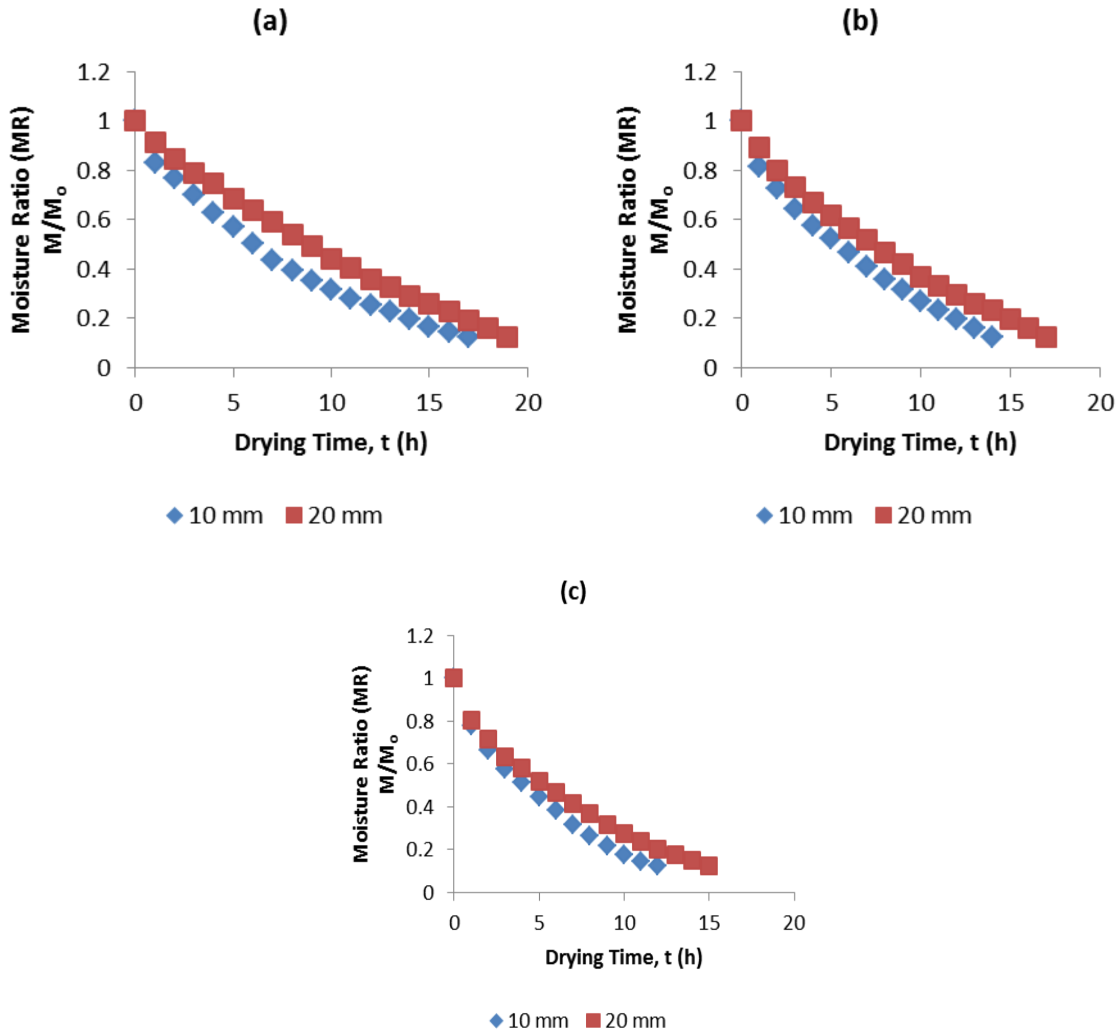

Figure 4: Moisture ratio variation with drying time for hot air drying of okra at
(a) 50 °C, (b) 60 °C, and (c) 70 °C

3.1 Modelling the drying kinetics

Experimental results of moisture variation with drying time were fitted to four different drying models known in literature as presented in Table 1. By using the non-linear regression tool of MATLAB 6.5 version computer software package, the parameters of the different models were determined. The model which provided the highest coefficient of determination (R^2) and the lowest root mean square error (RMSE) was selected. The values of R^2 and RMSE obtained by the non-linear regression analysis are summarized in Tables 2, 3 and 4 for okra slices dried under open sun, solar and hot air dryer respectively. The results in Tables 2, 3 and 4, respectively show that in all cases (different sample thickness), the value of R^2 was greater than 0.90, indicating a good fit (Madamba, 2003; Kingsly et al., 2007). However, the R^2 value for the logarithmic model at the different sample thicknesses under open sun drying (Table 2), solar drying (Table 3) and hot air drying (Table 4) was comparatively the highest and with the lowest RMSE value. Thus, the logarithmic model may be proposed to be the best model to describe the drying behavior of okra with different thickness dried under open sun, solar and oven dryer respectively. Similar findings have been reported for air drying of organic apple (Sacilik and

Elicin, 2006), whole figs (Xanthpoulos et al., 2007), sweet pepper (vengaiah and Pandey, 2007), and peach (Kingsly et al., 2007). The estimated values for the logarithmic model parameters are summarized in Table 5. The result showed that under open sun and solar drying of okra described by logarithmic model, the drying constant 'k' and the empirical constant 'c' is higher at a higher sample thickness, while the empirical constant 'a' is lower at a higher sample size. From Table 5 for the hot air drying of okra described by the logarithmic model, the result also showed that the drying constant 'k' and the empirical constant 'c' parameters of the model is relatively lower at a higher sample thickness; while the empirical constant 'a' is higher at a higher size. In addition, the drying constant 'k' and the empirical constant 'c' parameters of the model relatively increased with increase in drying temperature; while the empirical constant 'a' decreased with increase in drying temperature. The drying constant dependence on the drying temperature can be represented through Eq. (10) to Eq. (15), respectively:

For hot air-drying of 10 mm okra slices:

$$a = 1.164 - 0.002T \quad (R^2 = 0.98) \tag{10}$$

$$c = -0.221 + 0.003T \quad (R^2 = 0.97) \tag{11}$$

$$k = 0.065 + 0.000T \quad (R^2 = 0.99) \tag{12}$$

For hot air-drying of 20 mm okra slices:

$$a = 2.648 - 0.023T \quad (R^2 = 0.97) \tag{13}$$

$$c = -1.626 + 0.345 \ln T \quad (R^2 = 0.99) \tag{14}$$

$$k = 0.065 + 0.002T \quad (R^2 = 0.97) \tag{15}$$

The accuracy of the logarithmic model to simulate the drying curves of okra with different thicknesses under open sun, solar and hot air drying respectively was evaluated. In order to mathematically evaluate the simulation, the average relative error (%E) and coefficient of determination (R^2) were calculated from comparing the experimental moisture ratio and those given by the proposed model for the range of sample thicknesses considered. These results are shown in Table 5. Fig. 5 and Fig. 6 show the representation of the predicted (estimated) vs. experimental moisture ratio of okra during drying through logarithmic model for different sample thicknesses under open sun, solar and hot air drying, respectively. From Table 5, it is observed that the coefficient of determination (R^2) values are high and the mean relative error (%E) values are low below 10% for all the sample thicknesses studied under open sun, solar and hot air drying. Thus, the logarithmic model allowed an accurate simulation of the drying curves of okra for the whole range of sample thicknesses (10 and 20 mm) studied under open sun, solar and hot air drying, respectively; therefore, exhibiting a high concordance between experimental and predicted (estimated) moisture ratio.

Table 2: Values of drying model constants and statistical parameters for open sun drying of okra

Model	Sample Thickness(mm)	R^2	RMSE
Newton	10	0.9784	0.0375
	20	0.9967	0.0334
Page	10	0.9970	0.0150
	20	0.9967	0.0155
Henderson and Pabis	10	0.9784	0.0375
	20	0.9828	0.0334
Logarithmic	10	0.9977	0.0141
	20	0.9980	0.0189

Table 3: Values of drying model constants and statistical parameters for solar drying of okra

Model	Sample Thickness(mm)	R^2	RMSE
Newton	10	0.9778	0.0378
	20	0.9840	0.0315
Page	10	0.9594	0.0470
	20	0.9573	0.0516
Henderson and Pabis	10	0.9778	0.0378
	20	0.9840	0.0315
Logarithmic	10	0.9954	0.0204
	20	0.9962	0.0208

Table 4: Goodness of fit of the different drying models for okra hot air drying data

Model	Size (mm)	Drying Temperature (^{o}C)	R^2	RMSE
Newton	10	50	0.9959	0.0167
		60	0.9913	0.0241
		70	0.9907	0.0258
	20	50	0.9848	0.0327
		60	0.9933	0.0213
		70	0.9889	0.0270
Page	10	50	0.9963	0.0163
		60	0.9923	0.0227
		70	0.9940	0.0216
	20	50	0.9947	0.0199
		60	0.9946	0.0198
		70	0.9928	0.0226
Henderson and Pabis	10	50	0.9970	0.0147
		60	0.9936	0.0214
		70	0.9936	0.0223
	20	50	0.9870	0.0311
		60	0.9934	0.0219
		70	0.9932	0.0219
Logarithmic	10	50	0.9974	0.0140
		60	0.9946	0.0204
		70	0.9974	0.0149
	20	50	0.9994	0.0066
		60	0.9983	0.0114
		70	0.9977	0.0133

Table 5: Logarithmic model constant parameters and goodness of fit for hot air drying of okra slices

Drying method	Sample size (mm)	Drying temperature (°C)	Model Constants			R^2	$\%E$
			a	k	c		
Open Sun	10		1.272	-0.2493	0.0058	0.9850	0.035
	20		1.132	-0.1092	0.0066	0.9980	0.160
Solar	10		1.237	-0.2209	0.0069	0.9954	0.089
	20		1.115	-0.1138	0.0071	0.9976	0.062
Hot air	10	50	1.031	-0.0750	0.1041	0.9980	0.018
		60	1.011	-0.0419	0.1111	0.9970	0.051
		70	0.977	-0.0169	0.1193	0.9990	0.016
	20	50	1.509	-0.5230	0.0441	0.9994	0.007
		60	1.200	-0.2240	0.0704	0.9990	0.022
		70	1.043	-0.1507	0.0891	0.9990	0.006

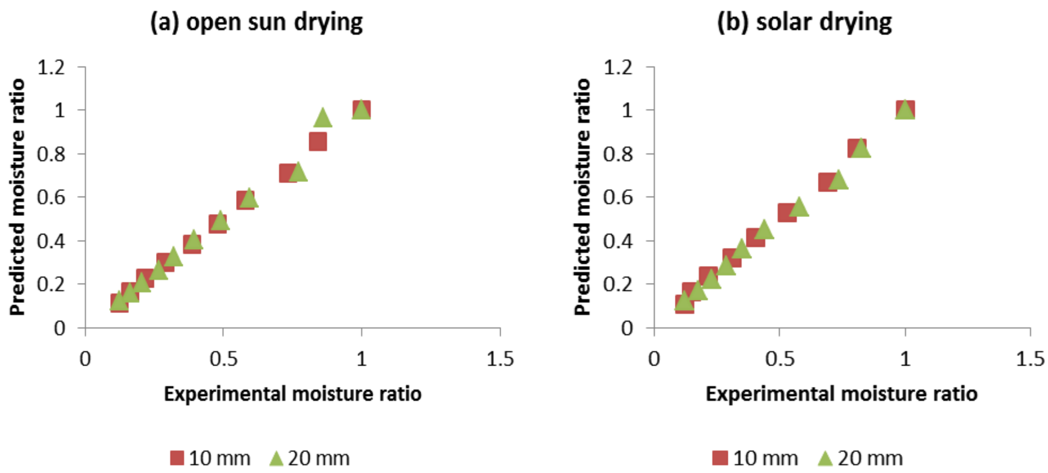

Figure 5: A plot of predicted and experimental moisture ratio values for (a) open sun drying and (b) solar drying of okra slices of 10 and 20 mm thickness

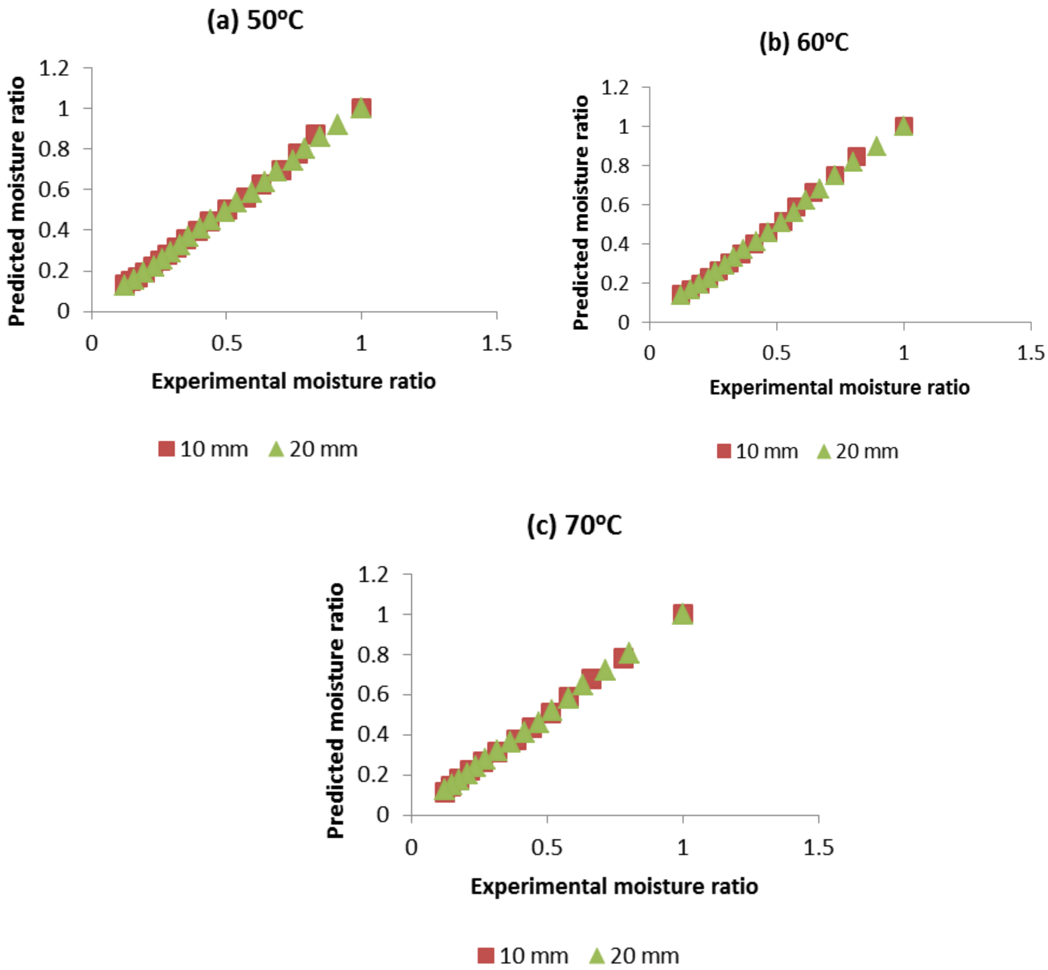

Figure 6: A plot of predicted and experimental moisture ratio values for hot air drying of okra slices of 10 mm and 20 mm thickness at (a) 50°C, (b) 60°C and (c) 70°C

3.2 Effective moisture diffusivity

The moisture transfer (water transport) during drying was described by applying the Fick's diffusion model. The experimental drying curves obtained at the different sample thicknesses (10 and 20 mm) under open sun and solar as well as at different sample thickness and drying temperature under hot air drying respectively was adjusted to the Fick's diffusion equation (equation 5). The good linear adjustment to this equation with coefficient of determination (R^2) ranging from 97-99% for the three different method of drying showed that drying of okra slices is well represented by the diffusion model proposed by Fick and this allowed for the calculation of the effective moisture diffusivity (D_{eff}) at the different sample thicknesses for open sun and solar as well as at different sample thickness and hot air drying temperature for hot air drying respectively. The results are presented in Table 6. The results show that the effective moisture diffusivity for okra slices with thicknesses (10 -20 mm) ranged from 0.253 to 0.901 × 10^{-10} m^2/s for open sun drying,0.310 to 1.011×10^{-10} m^2/s for solar drying and 3.19 to 14.7 x $10^{-11}$$m^2/s$ for hot air drying respectively. These values are within the general range 10^{-11} – $10^{-9}$$m^2/s$ for drying of food materials (Doymaz, 2005; Kaleemullah and Kailappan, 2006; Sacilik and Elicin, 2006; Doymaz, 2007; Honoŕe et al., 2014). The results in Table 6 showed that irrespective of the drying method, effective moisture diffusivity is higher at a higher sample thickness and also increased with increase in air drying temperature. A similar observation has been reported for increase in diffusivity coefficient as air drying temperature increases (Rahman and Kumar, 2007; Sobukola, 2009; Kadam et al., 2011; Khawas et al., 2014). The average effective moisture diffusivity of okra slices dried under hot air drying was comparatively higher than that dried under open sun and solar drying, respectively (Table 6).

Table 6: Values of effective moisture diffusivity for open sun, solar and hot air drying of okra slices

Drying method	Sample size (mm)	Drying temperature (°C)	Effective moisture diffusivity (D_{eff} × 10^{-10}) (m^2/s)	R^2
Open Sun	10		0.253	0.987
	20		0.901	0.994
Solar	10		0.310	0.988
	20		1.01	0.991
Hot air	10	50	3.29	0.996
		60	3.86	0.987
		70	4.76	0.995
	20	50	11.4	0.972
		60	12.7	0.981
		70	14.7	0.993

The activation energy and the Arrhenius constant were determined from the slope and the y-intercept, of the plot of $\ln D_{eff}$ against $1/T_{abs}$ (Fig. 7), respectively, and the values are presented in Table 7.

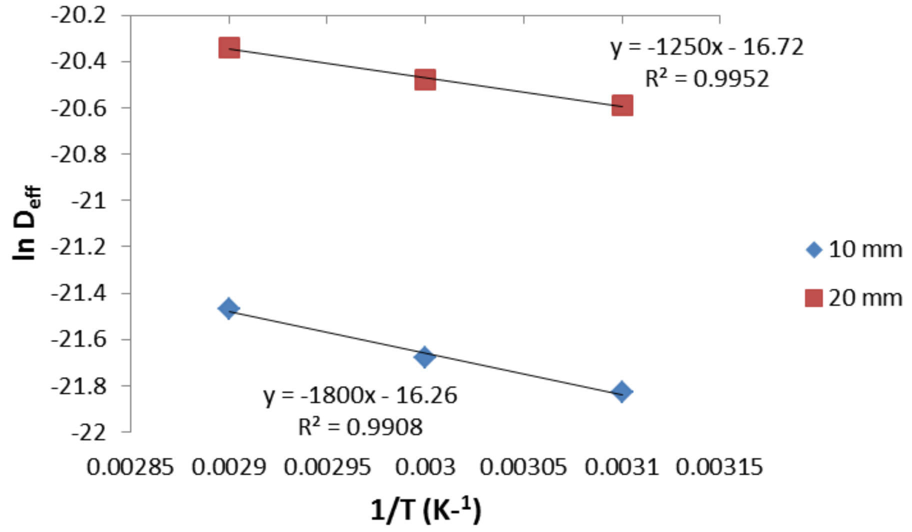

Figure 7: Arrhenius-type relationship between effective moisture diffusivity and the reciprocal of absolute temperature

The Arrhenius constant is a diffusivity constant equivalent to the diffusivity at infinitely high temperature. The activation energy is the energy barrier that must be overcome in order to activate moisture diffusion. By increasing the temperature and hence the drying rate this energy barrier can be easily overcome but there should be a compromise between high temperature and acceptable product quality (Kashaninejad et al., 2007; Hii et al., 2009). The values of D_o and E_a were estimated at 8.68 × 10^{-8} m^2/s and 14.97 kJ/mol for okra slice of 10 mm thickness and 5.48 × 10^{-8} m^2/s and 10.39 kJ/mol for okra slice of 20 mm thickness. Thus, the activation energy is lower at a higher sample thickness. The values of activation energy lie from 12.7 to 110 kJ/mol for most food material (Zogzaz et al., 1996). The values obtained in this present work compares relatively with the value of 12.32 – 14.34 kJ/mol obtained for potato by Senadeera et al. (2003), 19.96 kJ/mol for red apple (Kaya et al., 2007), and 16.749 and 22.437 kJ/mol for treated and untreated okra (Sobukola, 2009), respectively.

Table 7: Arrhenius constant and Activation energy of sliced okra

Sample size (mm)	Arrhenius constant D_o (m^2/s)	Activation energy (E_a) kJ/mol	R2
10	8.68	14.97	0.990
20	5.48	10.39	0.995

4.0 CONCLUSION

Drying rates and thus drying periods were affected by sample thickness under open sun and solar drying; and as well as sample thickness and drying temperature under hot air drying, respectively. Higher sample thickness resulted in higher drying times. The hot air drying method (forced convection air drying) resulted in a higher drying rate and faster drying time than the open sun and solar air drying (natural convection air drying). By using the semi empirical logarithmic model, sufficient description of the drying curves of okra under open sun, solar and hot air drying could be obtained and this could represent a useful tool for engineering purposes. The Fick's diffusion model showed a good linear adjustment to the experimental results obtained under open sun, solar drying and hot air drying which permitted the estimation of the effective moisture diffusivity. The estimated effective moisture diffusivities ranged from 0.253 to 0.901 × 10^{-10} m^2/s for open sun drying, 0.310 to 1.011×10^{-10} m^2/s for solar drying and 3.19 to 14.7 x 10^{-11}m^2/s for hot air drying respectively. The effective moisture diffusivities increased with air drying temperature following the Arrhenius type relationship. The values for D_o and E_a were estimated at 8.68 × 10^{-8} m^2/s and 14.97 kJ/mol for okra slice of 10 mm thickness and 5.48 × 10^{-8} m^2/s and 10.39 kJ/mol for okra slice of 20 mm thickness.

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