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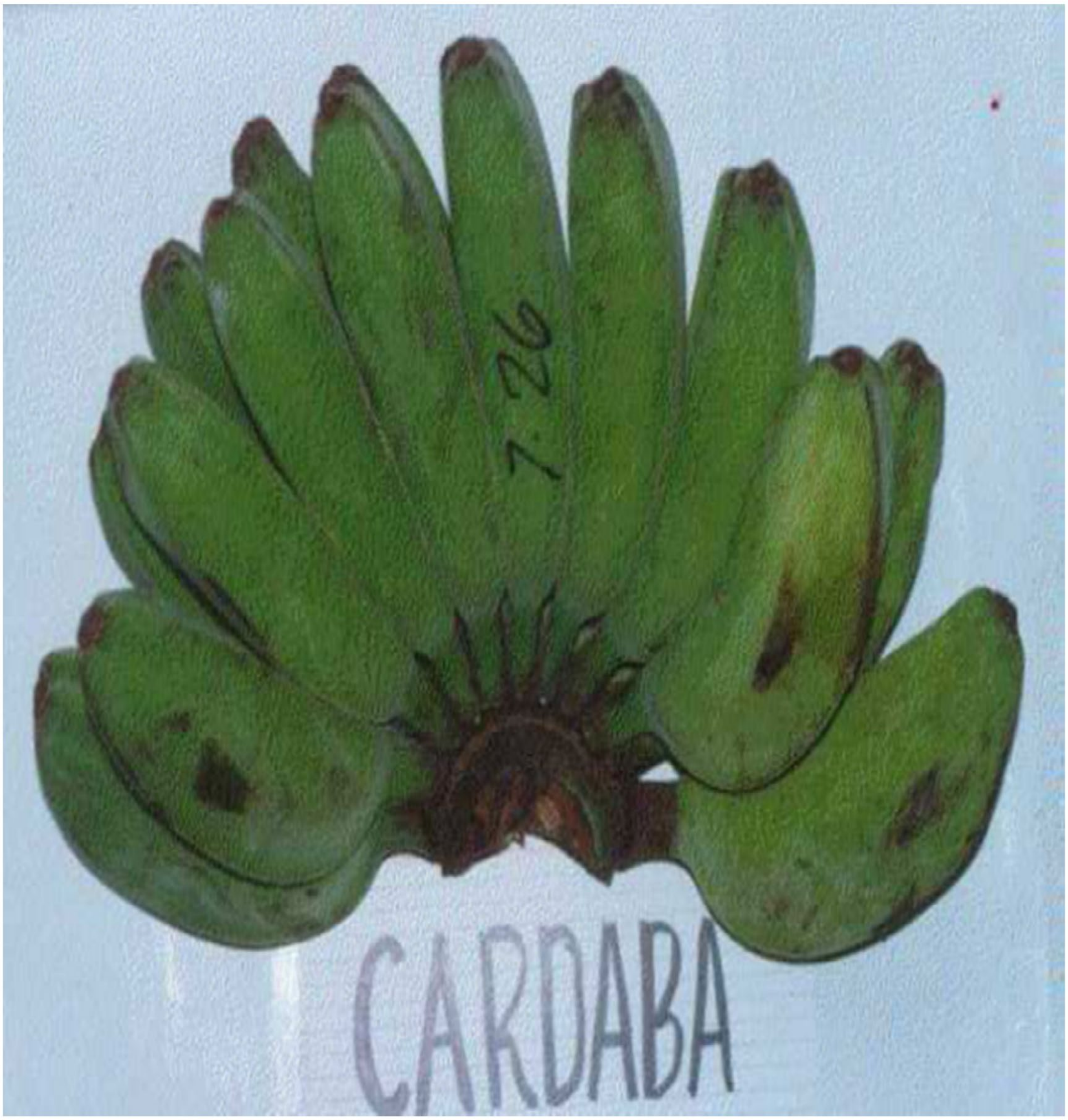

FOOD SCIENCE & TECHNOLOGY | RESEARCH ARTICLE

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Modelling of thin-layer drying characteristic of unripe Cardaba banana (*Musa* ABB) slices

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Abstract: In order to determine the behavior of Cardaba banana during drying, the thin layer drying kinetics were investigated using sun and hot air-drying at the temperature of 50, 60 and 70°C. The drying rate of the convective hot air oven was kept constant at 1.2 m²/s. The drying curves of the Cardaba banana slices contained no constant rate of drying but took place in the falling rate period. Twelve thin-layer drying model were used to fit the drying data and compared according to their coefficients of determination (R^2), root mean square error (RMSE) and reduced χ^2 to estimate drying curves. Among the thin-layer models, Wang and Singh model with R^2 of 0.9953, RMSE of 0.0223 and χ^2 of 4.94×10^{-4} was found to best explain the drying behavior of the Cardaba banana slices. Effective moisture diffusivity of Cardaba banana slices increased from 1.46×10^{-8} to 4.25×10^{-8} m²/s, resulting to activation energy of 38.46 kJ/mol. The results obtained proved that Wang model is an efficient thin-layer model that could be used in dryer designing of and processing of Cardaba banana.

Subjects: Food Science & Technology; Preservation; Processing

Keyword: thin layer; drying kinetics; activation energy; Cardaba banana; modelling

1. Introduction

The search for lesser known and under-utilized crops, many of which are potentially valuable as human and animal foods, has been intensified to maintain a balance between population growth and agricultural productivity in the world, one of such crops is Cardaba banana (*Musa* ABB). Cardaba banana (*Musa* ABB), a dwarf banana cultivar classified within the Saba subgroup is an under-utilized banana variety which is available throughout the year in Southern Nigeria. It is highly limited in utilization to production of flour and fried chips when unripe, thereby predisposing it to rapid

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PUBLIC INTEREST STATEMENT

Cardaba banana, primarily a cooking banana though it can also be eaten raw. However, the qualities of fresh banana deteriorate rapidly after harvesting and thus required drying operation for its preservation. In this present research, thin-layer drying characteristics of unripe Cardaba banana slice was carried out using hot air-oven at various temperature and constant air velocity. The experimental data obtained were used to determine the drying kinetics. Drying kinetics when coupled with some chemical analysis is helpful in predicting an effective drying time temperature combination, involving lesser degradation of nutrition parameters within a crop.

post-harvest losses attributed to lack of storage facilities, its physiological metabolic activities and high moisture content. The consumption and utilization of Cardaba banana has increased over the year owing to its cheaper price when compared to dessert bananas and plantains, its potential in the formation and the development of other food product like starch drinks, confectionaries and other bakery products (Olawoye & Kadiri, 2016). Owing to increase in the utilization of the crop and the formulation of a wide range of possible products from Cardaba banana, there is need to replace traditional open-air sun-drying with efficient drying system. This is because the drying rate of open-air or sun drying is relatively slow, it exposes the product to contamination and is difficult to control, thus resulting in a product of low quality. Thus, traditional drying techniques should be replaced with the industrial dryers such as solar and hot air dryers (Tunde-Akintunde & Oke, 2012). Drying is collective effect of heat-mass transfer phenomenon which brings about quality changes in dried food products. Therefore, knowledge about the physical and thermal characteristics of food and agricultural materials, such as moisture diffusion, heat and mass transfer, specific energy and activation energy consumption are necessary to understand the drying mechanics (Diamante & Yamaguchi, 2012). Thin-layer drying is a widely-used method for determining the drying kinetics of food and agricultural products (Alves-Filho, Strommen, & Thorbergsen, 1997; Chau, Mujumdar, Hawlader, Chou, & Ho, 1997; Kadam, Goyal, & Gupta, 2011; Kiranoudis, Tsami, Maroulis, & Marinos-Kouris, 1997). It involves simultaneous heat and mass transfer operations. During these operations, the food material is fully exposed to drying conditions of temperature and hot air, thus improving the drying process. Some researchers have studied thin-layer drying models of various agricultural and food products to predict the drying time and generalized the drying curve. Among these are peeled almonds (Ruiz-Beviá, Fernández-Sempere, Gómez-Siurana, & Torregrosa-Fuerte, 1999), banana peel (Kiranoudis et al., 1997), potato slices (Akpinar, Midilli, & Bicer, 2003), banana (Musa acuminate) (Pereira, Silva, & Gama, 2014), unripe plantain chips (Famurewa & Adejumo, 2015) and mango slice (Goyal, Kingsly, Manikantan, & Ilyas, 2006). However, there is little information on thin-layer modelling of Cardaba banana slices using natural and convectional drying methods. There is therefore, the need to study the thin-layer modeling of Cardaba banana in order to understand the drying process. The objective of this study is to established the drying kinetics of Cardaba banana slice dried using sun and convective oven dryer at 50 and 70°C and to fit data obtained from thin-layer drying of Cardaba banana to some generally accepted drying model.

2. Materials and methods

2.1. Materials

Matured unripe Cardaba banana was obtained in the month of August 2016 from teaching and research farm, Obafemi Awolowo University Ile-Ife, Osun state, Nigeria. Before the experiment, the matured Cardaba banana was thoroughly washed, peeled and subsequently sliced using fruit slicer into 5 mm thickness. The slices were measured using digital Vernier caliper (Kingsmart, UNSPSC 10234L) providing a precision of 0.02 mm for thickness accuracy. Approximately 400 g sample of matured unripe Cardaba banana were used for both drying operations (sun and oven drying). Drying of the Cardaba banana slices started at the initial moisture content and continued until three successive constant moisture content was obtained.

2.2. Experimental design

Sun drying experiment were carried out between the months of August and September 2016 in Ile-Ife, Osun state, Nigeria. The experimental set-up for the sun drying operation was performed using a wire mesh tray of 0.172×0.246 m^2 where the sliced Cardaba banana were placed. A schematic diagram of the set-up is shown in Figure 1. The sun drying process was between 8:00 am and 5:00 pm. Both the minimum and maximum daytime temperature together with the relative air humidity were measured and were 21°C, 38°C and 75% respectively with no rain. The initial and final moisture contents of the sliced Cardaba banana were determined using Association of Official Analytical Chemists (2000). Measurement was not recorded during the night. The experiment was performed three times for accurate result and the mean value was used.

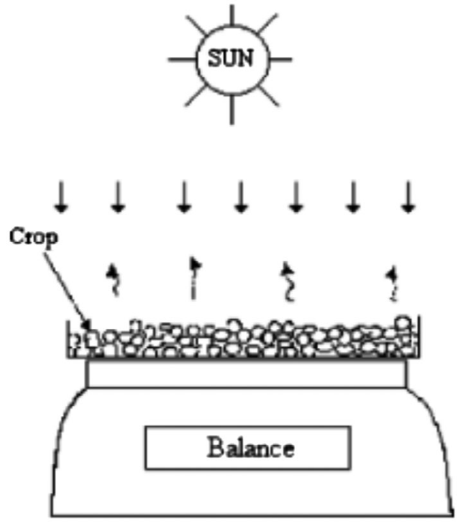

Figure 1. Experimental set-up for sun drying.

Source: Adapted from Toğrul and Pehlivan (2004).

2.3. Oven drying

Approximately 400 g of sliced Cardaba banana were spread in thin-layer inside a convective oven dryer which consists of airflow control unit, an electric fan, a heating and heating control unit and dryer chamber as shown in Figure 2. The experiment was conducted at the drying air temperature of 50, 60 and 70°C and constant drying rate of 1.2 m^2/s which was measured using vane probe anemometer (TESTO 440, Lutron, Taiwan). The anemometer was calibrated in accordance to ISO/IEC 17025, (2005) using oven method. Samples were weighed during the drying process using a digital balance with 0.001 g accuracy. The gravimetric method was used to determine the initial and final moisture contents of Cardaba banana samples at 50, 60 and 70°C during 24 h (American Society of Agricultural Engineers, 2007).

2.4. Data analysis

The moisture ratio (MR) of unripe mature Cardaba banana slices during the drying process was obtained using the following Equation (1):

$$\mathrm{MR} = \frac{M - M_e}{M_0 - M_e} \tag{1}$$

where M, M_0, and M_e are moisture content at any drying time (t), initial and equilibrium moisture content (kg water/kg dry matter), respectively. However, the value of M_e is relatively small when

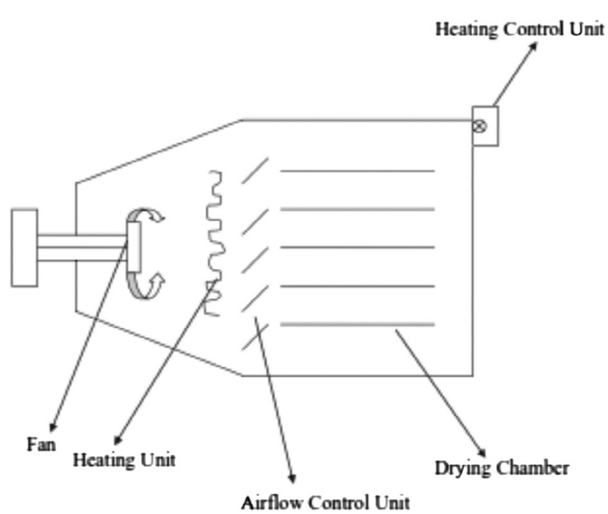

Figure 2. Schematic view of hot air-dryer.

Source: Adapted from Tunde-Akintunde and Oke (2012).

compared to those of M and M_0, hence it can be negligible (Famurewa & Adejumo, 2015), hence Equation (1) becomes:

$$MR = \frac{M}{M_0} \tag{2}$$

2.5. Thin-layer mathematical model of drying curves

Several researchers have predicted semi-theoretical and empirical models describing kinetic behavior of thin-layer drying process. Twelve thin-layer drying models were fitted to the drying curves so as to select the best model suitable for describing the drying curve of Cardaba banana. The models are presented in Table 1.

2.6. Nonlinear regression analysis

Nonlinear regression analysis was done using GraphPad prism 6 (GraphPad Software, Inc.). The goodness of fit was determined using three parameters: coefficient of determination (R^2), reduced χ^2, mean bias error and root mean square error (RMSE) using Equations (3)–(6) respectively (Toğrul & Pehlivan, 2002).

$$R^2 = \frac{\sum_{i=1}^{n}\left(\mathrm{MR}_i - \mathrm{MR}_{\mathrm{pre},i}\right) \times \left(\mathrm{MR}_i - \mathrm{MR}_{\mathrm{exp},i}\right)}{\left[\left[\sum_{i=1}^{n}\left(\mathrm{MR}_i - \mathrm{MR}_{\mathrm{pre},i}\right)^2\right] \times \left[\sum_{i=1}^{n}\left(\mathrm{MR}_i - \mathrm{MR}_{\mathrm{pre},i}\right)^2\right]\right]^{1/2}} \tag{3}$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(\mathrm{MR}_{\mathrm{exp},i} - \mathrm{MR}_{\mathrm{pre},i}\right)^2}{N - n} \tag{4}$$

$$\mathrm{RMSE} = \left[\frac{1}{N}\sum_{i=1}^{N}\left(\mathrm{MR}_{\mathrm{pre},i} - \mathrm{MR}_{\mathrm{exp},i}\right)^2\right]^{1/2} \tag{5}$$

Table 1. Thin-layer drying models selected for this study

Model No.	Model name	Model name	Reference
1	Lewis	$\mathrm{MR} = \exp(-kt)$	El-Beltagy, Gamea, and Essa (2007)
2	Page	$\mathrm{MR} = \exp(-kt^n)$	Akoy (2014)
3	Henderson and Pabis	$\mathrm{MR} = a\exp(-kt^n)$	Meisami-asl, Rafiee, Keyhani, and Tabatabaeefar (2010)
4	Modified page I	$\mathrm{MR} = \exp[-(kt)^n]$	Vega, Uribe, Lemus, and Miranda (2007)
5	Modified page II	$\mathrm{MR} = k \cdot \exp(-t/d^2)^n$	Praveen Kumar, Hebbar, and Ramesh (2006)
6	Wang and Singh	$\mathrm{MR} = 1 = at + bt^2$	Omolola et al. (2014)
7	Balbay and Sahin	$\mathrm{MR} = (1 - a) \cdot \exp(-kt^n) + b$	Balbay and Şahin (2012)
8	Hasibuan and Daud	$\mathrm{MR} = 1 - at^n \cdot \exp(-kt^n)$	Ertekin and Heybeli (2014)
9	Two term	$\mathrm{MR} = a \cdot \exp(-kt) + b.\exp(kt)$	Sacilik (2007)
10	Two-term exponential	$\mathrm{MR} = a \cdot \exp(-kt) + (1 - a)\exp(k.a.t)$	Dash, Gope, Sethi, and Doloi (2013)
11	Verma et al.	$\mathrm{MR} = a\,a \cdot \exp(-kt) + (1 - a)\exp(-gt)$	Akpinar (2006)
12	Modified Henderson and Pabis	$\mathrm{MR} = a \cdot \exp(-kt) + b \cdot \exp(-gt) + c \cdot \exp(-ht)$	Zenoozian, Feng, Razavi, Shahidi, and Pourreza (2008)

2.7. Determination of effective moisture diffusivity (D_{eff})
Fick's second law of diffusion equation was used for the calculation of effective moisture diffusivity of the dried Cardaba banana slices. It was based on the assumption that there is a uniform initial moisture distribution; moisture migration is by diffusion, negligible shrinkage, negligible external resistance, constant diffusion coefficients and temperature (Pala, Mahmutoglu, & Saygi, 2006). Fick's second law of diffusion equation for geometry slab was used and is expressed by Maskan, Kaya, and Maskan (2002):

$$\mathrm{MR} = \frac{8}{\pi^2} \exp \frac{-\pi D_{\mathrm{eff}} t}{4L^2} \tag{6}$$

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 metre. The diffusion coefficient was obtained by plotting experimental drying data in terms of Ln(MR) against drying time. The effective diffusivity, D_{eff} was evaluated using method of slopes (Doymaz, 2010; Maskan et al., 2002).

Thus, the equation of effective diffusivity of the Cardaba banana becomes:

$$\text{Slope } K = \frac{D_{\mathrm{eff}} \pi^2}{4L^2} \tag{7}$$

2.8. Determination of activation energy
The relationship between effective diffusivity and drying temperature can be predicted appropriately using Arrhenius equation (Akpinar, 2006; Sacilik, 2007). The activation (E_a) can be determined using Equation (8):

$$D_{\mathrm{eff}} = D_0 \exp \left(-\frac{E_a}{R(T + 273.15)} \right) \tag{8}$$

where D_{eff} is the effective moisture diffusivity (m^2/s), D_0 is the pre-expeonential factor of Arrhenius equation (m^2/s), E_a is the activation energy in KJ/mol, R is the universal gas constant in KJ/mol K and T is the drying temperature. Equation (8) can be re-written as:

$$\ln(D_{\mathrm{eff}}) = \ln(D_0) + \left(-\frac{E_a}{R(T + 273.15)} \right) \tag{9}$$

The activation energy can be obtained by plotting ln D_{eff} against $\left(-\frac{1}{(T+273.15)}\right)$ which give a slope, K:

$$\text{The activation energy is therefore } E_a = \mathrm{KR} \tag{10}$$

where R is 0.00831447 KJ/mol K.

3. Result and discussion

3.1. Drying characteristics
A single layer Cardaba banana samples were dried in the sun and hot air oven drier at temperature of 50, 60 and 70°C. The Cardaba samples had a thickness of 5 mm and the initial moisture content of about 79.80% wb (395.05% db) were dried to the final moisture content of 13.61, 11.34, 9.10 and 8.47% db for drying using sun, 50, 60, and 70°C, respectively. The moisture content of the Cardaba banana samples decreased at temperatures of 50, 60 and 70°C with a variation drying rate which exhibit a falling rate of drying which is the main drying mechanism in controlling the water evaporation rate. Figure 3 illustrates the changes in moisture ratio against drying time of banana slices dried under sun and at three different oven-drying temperatures. It could be observed that the time elapses for the drying of the Cardaba banana samples decreases with increasing temperature (i.e. sun < 50 < 60 < 70°C) while the moisture ratio decreases incessantly with drying time. The higher drying time required to remove the moisture content in the Cardaba banana slices could be as a

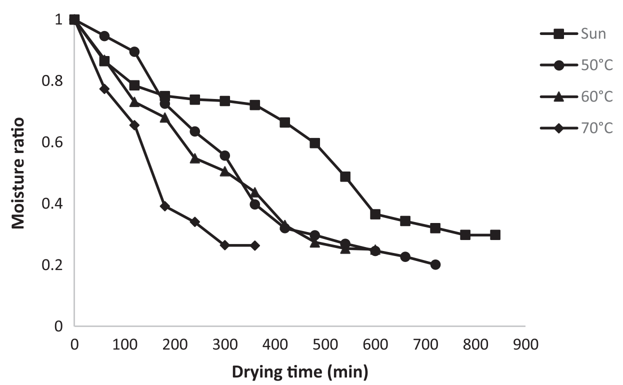

Figure 3. Drying curves for Cardaba banana using open sun and hot air oven at 50, 60 and 70°C.

result of slow diffusion process. This result correlates with previous studies reported for various food materials such as tigernut (Tunde-Akintunde & Oke, 2012), culinary banana slices (Khawas, Das, Dash, & Deka, 2014), banana slices (Prachayawarakorn, Thuwapanichayana, & Kunwisawa, 2011) and blanched pumpkin slices (Olurin, Adelekan, & Olosunde, 2012).

3.2. Modelling of drying curves

The moisture content data obtained from drying of Cardaba banana slices using sun and different air drying temperature was converted to moisture ratio and was fitted to twelve different thin-layer drying models which are presented in Table 2 along with the statistical analysis of the model. The

Table 2. Statistical results obtained from selected thin-layer models

Model No.	Temperature (°C)	Constants	*R*	RMSE	χ^2
1	Sun	$k = 0.0812$	0.9225	0.0639	0.00408
	50	$k = 0.1335$	0.961	0.058	0.0404
	60	$k = 0.14645$	0.9918	0.0233	5.46×10^{-4}
	70	$k = 0.2578$	0.977	0.0435	0.00189
2	Sun	$k = 0.05673, n = 1.167$	0.9295	0.0663	0.004
	50	$k = 0.0778, n = 1.286$	0.9813	0.0421	0.00177
	60	$k = 0.1361, n = 1.042$	0.9924	0.0238	5.64×10^{-4}
	70	$k = 0.2577, n = 0.9998$	0.977	0.0477	0.00227
3	Sun	$a = 0.9956, k = 0.0810$	0.9225	0.0663	0.00439
	50	$a = 1.080, k = 0.1467$	0.9738	0.0498	0.00248
	60	$a = 1.007, k = 0.1478$	0.992	0.0244	5.97×10^{-4}
	70	$a = 1.004, n = 0.2590$	0.9738	0.0476	0.00227
4	Sun	$k = 0.08546, n = 1.167$	0.9294	0.0663	0.00399
	50	$k = 0.1372, n = 1.2846$	0.9795	0.0568	0.00323
	60	$k = 0.1474, n = 1.041$	0.9918	0.0246	5.64×10^{-4}
	70	$k = 0.2577, n = 0.9943$	0.9747	0.0499	0.00227
5	Sun	$k = 0.185, d = 1.660, n = 1.167$	0.9295	0.0658	0.00433
	50	$k = 0.372, d = 1.837, n = 1.285$	0.9813	0.0441	0.00195
	60	$k = 4078, d = 1.692, n = 1.042$	0.9924	0.0252	6.35×10^{-4}
	70	$k = 0.6443, d = 1.5812, n = 0.995$	0.9770	0.0553	0.00284
6	Sun	$a = -0.06327, b = 7.28 \times 10^{-4}$	0.9406	0.058	0.00336
	50	$a = -0.1133, b = 0.0037$	0.9732	0.0503	0.00253
	60	$a = -0.1331, b = 0.0058$	0.9953	0.0223	4.97×10^{-4}
	70	$a = -0.24522, b = 0.020$	0.9723	0.0477	0.00227

(*Continued*)

Model No.	Temperature (°C)	Constants	*R*	RMSE	χ^2
7	Sun	*a* = −1.153, *k* = 0.00043, *n* = 0.9987, *b* = −1.53	0.9500	0.0579	0.00334
	50	*a* = 0.215, *k* = 0.0467, *b* = 0.2098, *n* = 1.864	0.9913	0.0232	5.40×10^{-4}
	60	*a* = 0.0959, *k* = 0.1337, *n* = 1.084, *b* = 0.0055	0.9924	0.0269	7.23×10^{-4}
	70	*a* = 0.2367, *k* = 0.2684, *b* = 0.2270, *n* = 1.433	0.9851	0.0495	0.00245
8	Sun	*a* = 0.05483, *n* = 0.3716, *k* = 0.6157	0.9533	0.0536	0.00316
	50	*a* = 0.0527, *n* = 1.550, *k* = 0.0247	0.9936	0.0259	6.69×10^{-4}
	60	*a* = 1345, *n* = 1.022, *k* = 0.0574	0.9928	0.0246	6.05×10^{-4}
	70	*a* = 0.2135, *n* = 1.2793, *k* = 0.0247	0.9936	0.0404	0.00163
9	Sun	*a* = 0.4978, *k* = 0.0809, *b* = 0.4978	0.9225	0.0689	0.00478
	50	*a* = 0.5398, *k* = 0.1467, *b* = 0.5398	0.9685	0.0522	0.00272
	60	*a* = 0.5034, *k* = 0.1477, *b* = 0.5031	0.9920	0.0259	6.72×10^{-4}
	70	*a* = 0.5020, *k* = 0.2590, *b* = 0.5120	0.9770	0.0529	0.00283
10	Sun	*a* = 1.6993, *k* = 0.1159	0.9329	0.0662	0.038
	50	*a* = 1.9003, *k* = 0.2101	0.9816	0.0607	0.00272
	60	*a* = 1.463, *k* = 0.1735	0.9918	0.0246	5.56×10^{-4}
	70	*a* = 0.5552, *k* = 0.3342	0.9728	0.0472	0.00283
11	Sun	*a* = 13.82, *k* = 0.1424, *g* = 0.1489	0.9337	0.0638	0.0402
	50	*a* = 1.229, *k* = 0.1689, *g* = 1.191	0.9882	0.0351	0.00123
	60	*a* = 1.244, *k* = 0.1668, *g* = 0.2936	0.9925	0.025	6.79×10^{-4}
	70	*a* = 1.0563, *k* = 0.423, *g* = 0.2659	0.9832	0.0455	0.00207
12	Sun	*a* = 0.3319, *b* = 0.332, *k* = 0.081, *g* = 0.081, *c* = 0.332, *h* = 0.081	0.9225	0.0796	0.00634
	50	*a* = 0.358, *b* = 0.359, *k* = 0.147, *g* = 0.147, *c* = 0.400, *h* = 0.147, *c* = 0.359	0.9738	0.0624	0.00389
	60	*a* = 0.336, *b* = 0.338, *k* = 0.148, *g* = 0.148, *h* = 0.147, *c* = 0.331	0.9923	0.0253	0.00107
	70	*a* = 0.508, *b* = 0.505, *k* = 0.271, g = 0.269, *h* = −3.114, *c* = 0.611	0.9837	0.0896	0.00802

Table 2. (*Continued*)

criterion for selection of the best model to describe the thin layer drying behavior of the banana slices was based on the highest correlation coefficient (R^2), the root mean square error (RMSE) and least of the reduced χ^2 values (Demir, Gunhan, Yagcioglu, & Degirmencioglu, 2004; Erenturk, Gulaboglu, & Gultekin, 2004; Goyal et al., 2006; Sarsavadia, Sawhney, Pangavhane, & Singh, 1999; Toğrul & Pehlivan, 2002). As presented in Table 1, the values of the R^2, RMSE and χ^2 for all the drying models and drying temperatures ranged from 0.9225 to 0.9953, 0.0222 to 0.0896 and 4.94×10^{-4}, respectively. According to these results, the model that best fit the experimental data using previously stated criterion (i.e. highest coefficient of determination (R^2), lowest RMSE and χ^2) for sun drying was Hasibuan and Daud with $R^2 = 0.9533$, RMSE = 0.0536 and $\chi^2 = 0.00316$ while that of hot-air drying was Wang and Singh model with $R^2 = 0.9953$, RMSE = 0.0223 and $\chi^2 = 4.94 \times 10^{-4}$. Based on these results, Hasibuan and Daud model was chosen as the suitable model to predict the thin-layer drying behavior of sun drying while Wang and Singh model was found suitable for hot-air drying of Cardaba banana. These findings agreed to previous study reported by Omolola, Jideani, and Kapila (2014) and Fadhel, Abdo, Yousif, Zaharim, and Sopian (2011) for banana slices and also to the report of Famurewa and Adejumo (2015) for plantain chips. Apart from Wang and Singh model, other model presented in Table 2 also described the thin-layer drying behavior of the Cardaba banana

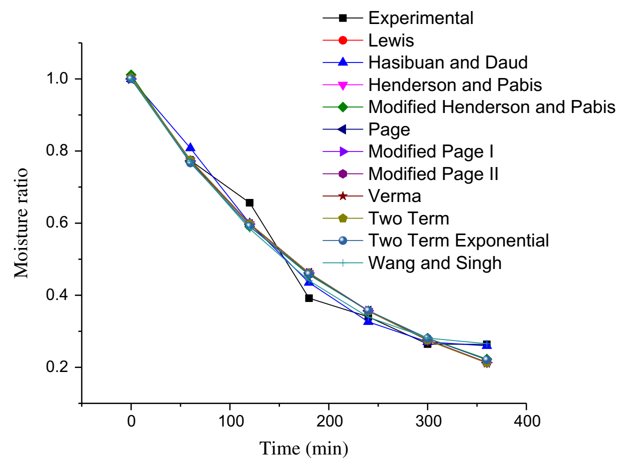

Figure 4. Comparison of the selected models fitted for Cardaba banana at 70°C.

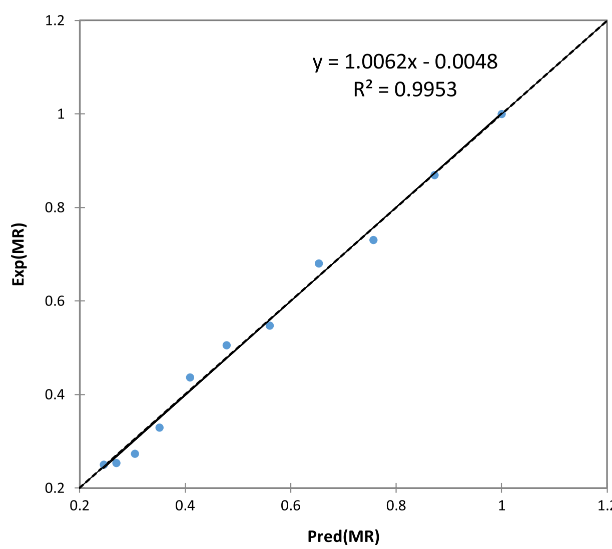

Figure 5. Plot of experimental moisture against predicted moisture ratio from Wang and Singh model.

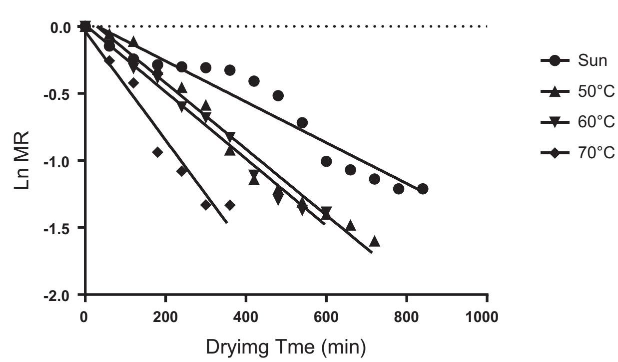

Figure 6. Plot of ln MR against drying time used in obtaining D_{eff}.

slices. Figures 4 and 5 showed conformity between the experimental and predicted moisture ratio values as the both laid around straight for Wang and Singh model. By considering the constants and factors of Wang and Singh model ($a = -0.1331$, $b = 0.0058$). The moisture ratio of the Cardaba banana slices at different stages of drying could be predicted successfully using the following equation.

$$MR = 1 + -0.133063943473219 \times t + 5.75534338743906E\text{-}03 \times t^2$$

Table 3. Effective moisture diffusivity values obtained at different drying conditions

Temperature (°C)	Effective moisture diffusivity (m^2/s)
Sun	1.46×10^{-8}
50	2.33×10^{-6}
60	2.53×10^{-6}
70	4.25×10^{-6}

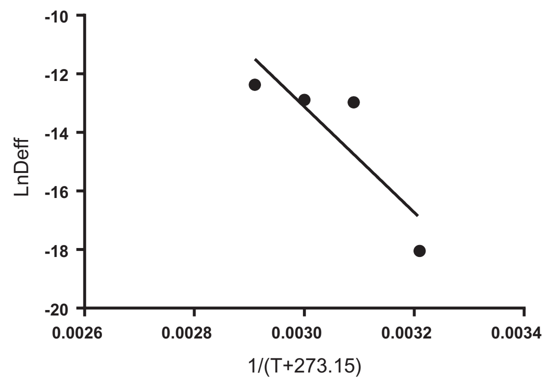

Figure 7. The Arrhenius relationship between diffusivities and absolute temperature.

3.3. Determination of the effective moisture diffusivity

Analysis of the falling rate period was performed to understand the drying kinetics and to determine the effective moisture diffusivity (D_{eff}) by slope method (Equation (3)) and this reviews that the mass transfer during drying operations is controlled by internal diffusion (Babalis & Belessiotis, 2004). The relationship between ln MR with respect to time is illustrated in Figure 6 and the calculated values of D_{eff} for all the temperatures (sun −70°C) are shown in Table 3. This result revealed that sun drying had the lowest D_{eff} value of 1.46×10^{-8} while drying at 70°C had the highest value of D_{eff} (4.25×10^{-6}). In general, D_{eff} increases with increase in drying temperature, thus temperature has a positive influence on moisture diffusivity. Doymaz (2010) also reported an increase in moisture diffusivity of banana (Cavendish) slices with an increased drying temperature. The value obtained in this study is however, slightly higher that values reported by Doymaz (2010), da Silva, Rodrigues, Silva, De Castro, and Gomes (2015) and Khawas, Das, Dash, and Deka (2015) which are 7.37×10^{-11}–2.15×10^{-10}, 5.25×10^{-10}–9.25×10^{-10}, and 5.61×10^{-9}–8.38×10^{-9}, respectively. This variation in values could be attributed to difference in location and growth condition, levels of maturity, drying equipment and other parameter that cannot be controlled.

3.4. Activation energy

The activation energy which is the minimum energy required to initiate moisture diffusion from the food products is obtained by applying Equation (9) for the Cardaba banana drying data at various air-drying temperatures. Plotting the graph of In D_{eff} against inverse of absolute temperature as revealed in Figure 7 showed a slightly high correlation of 0.7513 indicating a good fit. The value of the activation energy obtained in this study was 38.46 $KJmol^{-1}$. The value obtained is however higher when compared with the value reported by Doymaz (2010) for banana slices. The differences observed could be related to lower temperature (i.e. 40–65°C) used in their study.

4. Conclusion

The drying kinetics characteristics of Cardaba banana slices with a thickness of 5 mm were investigated in sun and convective hot air dryer at the drying air temperature of 50, 60 and 70°C. The convective hot air drying of the Cardaba banana slices resulted in decreased in drying time with an increase in the drying temperature. Of the twelve thin-layer mathematical model selected to stimulate the experimental drying data, Wang and Singh model with R^2 of 0.9953, RMSE of 0.0223 and χ^2 of 4.94×10^{-4} was considered the best model for describing the drying behavior of Cardaba banana slices. Effective moisture diffusivity of Cardaba banana slices increased from 1.46×10^{-8} to 4.25×10^{-8} m^2/s, resulting to an activation energy of 38.46 kJ/mol. The effective moisture diffusivity and activation energy values obtained in this study were in accordance with the minimum energy of other food products in a general range reported by several researchers.

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